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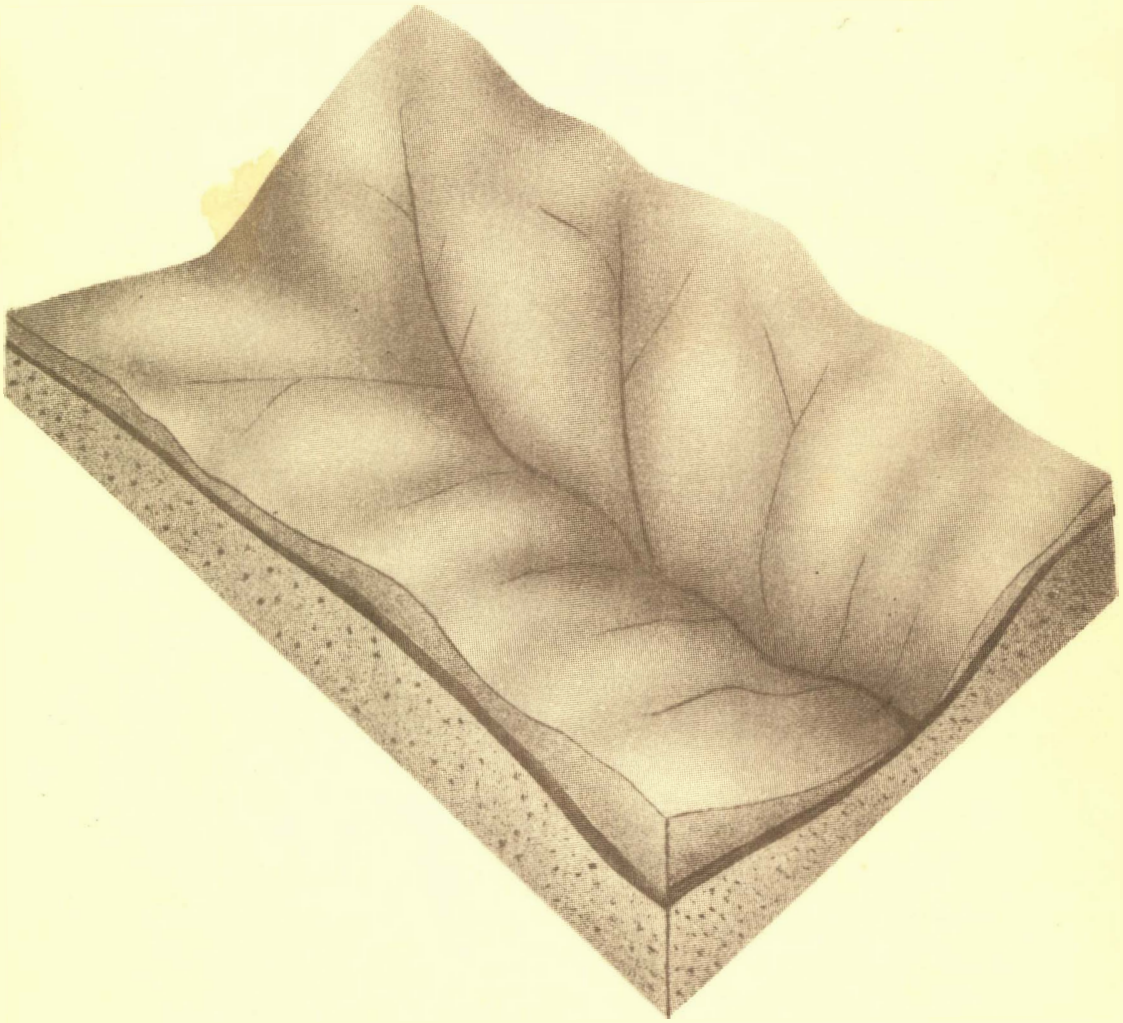
Morphometric Indices of Streamflow and Sediment Yield From Mountain Watersheds in Western Oregon



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December 31, 1978

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MORPHOMETRIC INDICES OF STREAMFLOW AND SEDIMENT YIELD FROM MOUNTAIN WATERSHEDS IN WESTERN OREGON

A Report Prepared for

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MORPHOMETRIC INDICES OF STREAMFLOW AND SEDIMENT YIELD FROM MOUNTAIN WATERSHEDS IN WESTERN OREGON

ABSTRACT. Systems analysis of fluvial form and process is used as a basis for determining significant statistical correlation between morphometric variables and streamflow and sediment yield. Seventy-two basin and stream network morphometric variables are measured for fifteen small, instrumented watersheds in mountain regions of western Oregon. A comprehensive review of the literature reveals eleven morphometric variables which have been used with some success to estimate annual runoff, base flows, peak flows, and sediment production on an area-yield basis. The most useful estimate of mean annual runoff is provided by drainage density (r^2 = .735). Relief ratio is the single most useful estimate of base flow (r^2 = .471). The most useful estimate of mean annual peak flow is provided by stream frequency (r^2 = .487). Drainage density is the single most useful estimate of mean annual sediment yield (r^2 = .425). Significant correlations are graphically displayed for additional variables. Some correlations are restricted to specific physiographic land types. Interpretation of the derived relationships is discussed relative to their usefulness as a tool in land management planning for the Siuslaw National Forest.

INTRODUCTION

Modeling hydrologic and erosional processes from lands in western Oregon managed by the U.S. Forest Service is necessary to identify potential hazard areas with respect to the quanitity, quality, and timing of streamflow. The purpose of this study is to select morphometric variables to be used for modeling mean annual runoff, base flow, mean annual peak flow, and mean annual sediment yield in land management planning for the Siuslaw National Forest. Morphometric measurements are physical descriptors of the drainage basin, hillslopes, stream network, channel reach, and channel cross section. Only basin and stream network morphometric variables will be considered in the present study since these can be measured from topographic maps and/or aerial photos without costly field surveys. The use of morphometric variables to estimate streamflow and sediment yield is predicated on the notion that basin and stream network morphology have adjusted over geologic time to climatic and lithologic factors and therefore reflect the magnitude and frequency of hydrologic and erosional processes.

Seventy-two basin and stream network morphometric variables were measured for fifteen small instrumented watersheds in mountain regions of western Oregon, representing a variety of physiographic settings. The streamflow and sediment data for the study basins were not necessarily collected during concurrent time periods except for paired watersheds. Only data from the period of record before watershed treatment were used in order to exclude the influence of land management practices. All data were normalized on an area-yield basis for greater applicability of results to resource planning. Linear correlation analysis was limited to two variables in order to avoid some problems with using multiple correlation techniques with hydrologic data.

Although a literature review of pertinent morphometric studies is included in the text of the report, mention is made here of three noteworthy publications. An article by Gardner and Park (1978) reviews the early foundations of morphometric studies, the contributions of R.E. Horton, the extension and refinement of Horton's techniques by Strahler and others, the concern over data measurement and interpretation, and applied uses of morphometric analysis, including predictive modeling of hydrologic and erosional processes. A collection of papers edited by S.A. Schumm (1977) allows the reader to examine key articles which have led to the state-of-the-art in morphometric studies, including reprints of several articles which address the arguments of the present study. A book by Gregory and Walling (1973) provides a comprehensive review of measurement and analytical techniques used to study drainage basin morphology.

The following pages will use systems analysis of fluvial form and process as a basis for determining the physical and statistical relationship between morphometric variables and stream flow characteristics and sediment yield. First, several fundamental concepts to morphometric studies will be outlined, including cartographic problems peculiar to morphometric analysis. Second, the study areas will be described. Third, basin and stream network morphometric variables will be listed and defined along with a review of measurement techniques and a discussion of the physical relevance of the variable to prediction of

hydrologic and erosional processes. Fourth, morphometric variables used to predict streamflow characteristics and sediment yield will be reviewed as reported in the literature. Fifth, morphometric analysis will be performed on the study basins and statistical correlations will be presented. The statistical limitations of the derived relationships will be discussed with respect to usefulness as a tool in forest-wide planning.

FUNDAMENTAL CONCEPTS OF MORPHOMETRIC ANALYSIS

Systems analysis of fluvial form and process provides the foundation for predictive modeling. Morphometric studies are largely controlled by the quality of topographic information, measurement techniques, and method of statistical analysis employed.

Systems Analysis and Predictive Modeling

Morphometric analyses of basin and stream network morphology (form) provide useful data at any scale of planning which recognizes the drainage basin as the fundamental planning unit. The drainage basin (or watershed, catchment) is a classic example of a hydrologic and geomorphic system because the boundaries are relatively discrete and the inputs and outputs can be measured with some degree of accuracy. Chorley (1962) notes that geomorphic systems should be considered as open systems, although certain features of closed systems may apply. The open system framework accounts for the following:

1) There is a need of energy supply for maintenance of the system;
2) there is a possibility that the system may reach an equilibrium condition characterized by self-regulation; and
3) different initial conditions can lead to similar end results.

To these features of open systems, Leopold and Langbein (1962) add that several geomorphic forms can be explained as conditions of the "most probable distribution of engergy." This developement toward maximum entropy, with a minimum rate of energy expenditure, is an upshot of the Davisian closed systems approach where the potential energy of a system tends toward zero. The evolution of stream networks has been cited as an example of increasing entropy in fluvial systems.

The systems approach to fluvial processes encourages quantitative analysis of form and process. Basin and stream network morphology is considered to interact with hydrologic and erosional processes. It is not clear whether one attribute is the cause of the other so morphometric variables will be considered simply as indices of streamflow characteristics and sediment yield if a significant statistical relationship can be established. The relationship between a morphometric variable and either annual runoff, low flows, peak flows, or sediment yield can be described by a regression equation defining a line which best fits a graphical presentation of the data points. The best-estimating equation comprises a process-response model because it relates an element of the morphological system (i.e. a morphometric variable describing basin or stream network morphology) to an element of the cascading system (i.e. streamflow or sediment yield) which involves a transfer of mass and energy. There are two principle types of models (Figure 1). Descriptive models include maps or a single statistic. Predictive models involve a forecast of system attributes, through time and/or space. The process-response models in the present study are normative in that they forecast what ought to occur when the selected morphometric variables are applied to ungaged basins. In other words, normative models derived in the following pages will provide an estimate of mean annual runoff, base flow, mean annual peak flow, or mean annual sediment yield in a different spatial context given a certain morphometric measurement. One must assume that the model accounts for temporal variability in the variables, an important assumption considering the non-concurrent periods of record for streamflow and sediment data in the study basins.

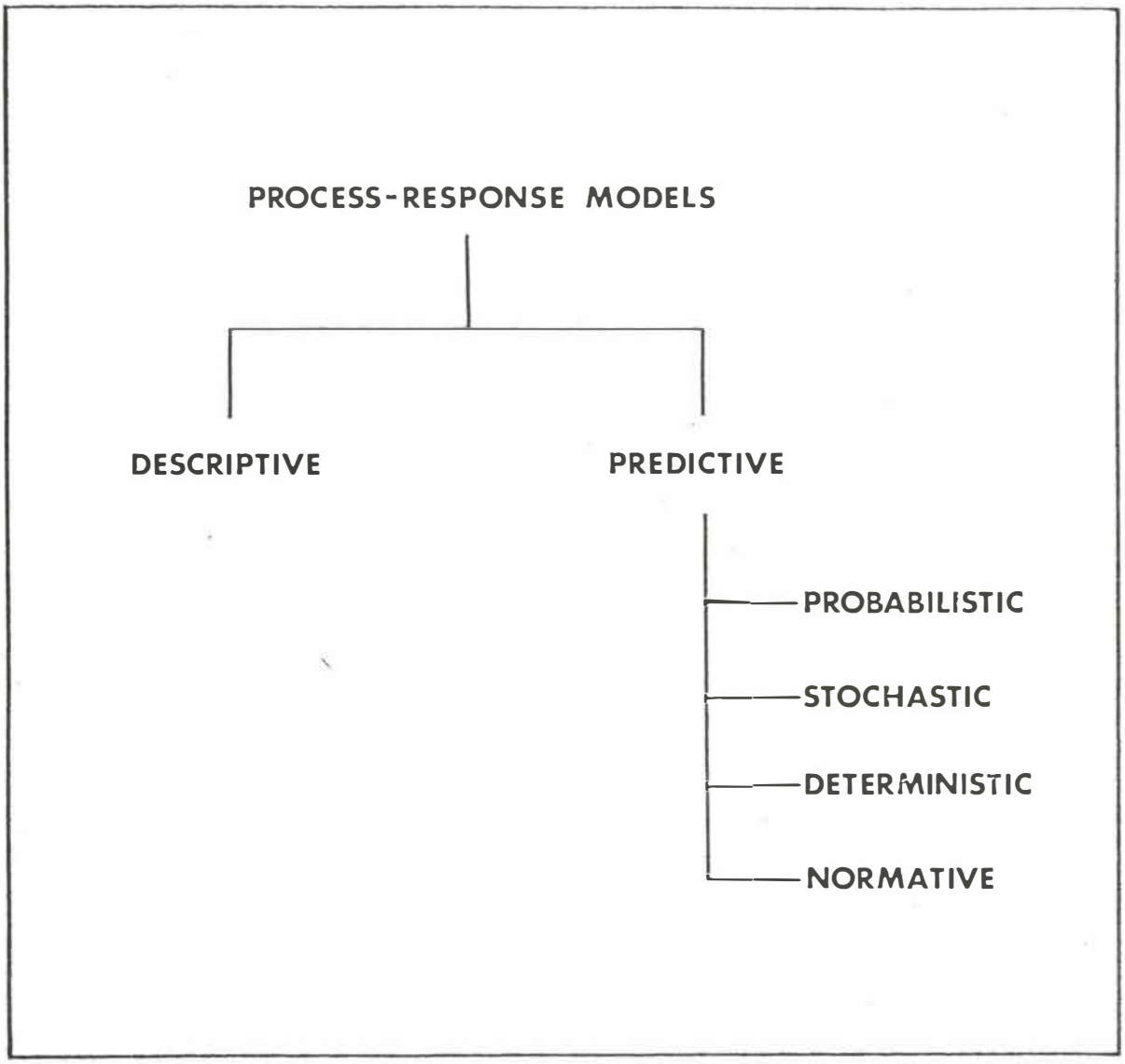

Figure 1. Models simulate reality in order to facilitate comprehension of complex relationships in nature. All models, including process-response models, may be classified as either descriptive or predictive. The latter involves some forecast of system attributes in time and/or space. Probabilistic models are time-independent. Stochastic models are time-dependent but assume that future events will have the same properties as those recorded in the past. Deterministic models do not consider probability because the outcome is certain and foreseeable if certain conditions are fulfilled. Normative models attempt to forecast what ought to occur under certain conditions, the intent of the present study using morphometric variables to estimate streamflow characteristics and sediment yield.

Cartographic Problems in Morphometric Analysis

The foremost prerequisite of morphometric studies is the availability of detailed and accurate topographic maps to minimize observer error with stream network delineation and measurement. Moreover, comparisons between basins require use of a consistent map scale and similar contour intervals. Measurement techniques must be explicit to prevent bias between observers. These problems have been explored by Jennings (1967). Yang and Stall (1971) found that stream order designations are dependent on the scale of the topographic map used, but bifurcation ratio, stream length ratio, and stream concavity measurements are independent of map scale. They note that if the difference in stream order designations among various map scales is known, an integer correction factor can be applied. This approach was used by Leopold and Miller (1956) who found that an arroyo designated as a first-order stream on a map of scale 1:24,000 became a fifth-order stream on a map of scale 1:2,400. This correction factor becomes cumbersome when applied to all other stream network morphometric measurements. Thus, use of a consistent map scale is recommended. Statistical comparisons of morphometric measurements from two groups of inexperienced operators using the same map scale has revealed little or no variation except in the recognition of first-order stream channels (Chorley, 1958).

There are several methods of stream network delineation, each with advantages and disadvantages. Langbein (1947) conducted one of the earliest morphometric studies using the blue lines on U.S. Geological Survey topographic maps as comprising the stream network. Chorley and Dale (1972) have quoted the U.S.G.S. specifications for blue-line mapping:

> All perennial drainage is shown regardless of length. Intermittent drainage spurs less than 2000 feet long usually are omitted unless they emanate from springs or bodies of water. As a general rule, for 1:24,000 and 1:62,500 scale maps those streams selected for publication should be shown as starting not closer than about 1000 feet from the divide or drainage head.

McCoy (1971) has found the U.S.G.S. "blue-line method" to be the weakest and most inconsistent delineation of the stream network. Field surveys are certainly the most accurate, but are costly and time-consuming, and impractical for regional morphometric studies. Aerial photos corrected for tilt have been used to delineate stream networks but variation due to vegetal cover strongly influences the definition of first order streams. Incised channels in clearcut units are much more distinct than in forested areas, a situation likely to induce bias on the part of the observer. A final method of stream network delineation utilizes the crenulation (or bend) of contours. Streams are defined where the bend of contours "point" upstream until a critical angle of contour bend is encountered. Defining this critical angle is difficult and necessarily imparts some subjectivity to stream mapping. Some researchers advocate the construction of a drainage mesh to avoid this problem, requiring the extension of all first order streams to the drainage boundary. However, this gives a distorted impression of the actual incised channel network which contributes to streamflow and sediment production. However, Gregory (1966), Morisawa (1957), and others agree that mapping stream networks by the contour crenulation method is at least as accurate as using air photos and is perhaps less arbitrary. This method is facilitated by the availability of topographic maps with detailed and accurate contour information. Several guidelines serve to reduce observer bias:

1) Extend streams up to, but not beyond, the contour with a definite bend, indicating an incised channel as opposed to a general depression in the landscape;
2) do not sketch any first-order streams unless they touch at least two contours;
3) use identical map scales for comparisons between basins;
4) use maps with similar contouor intervals (+/-20 feet); and
5) do not sketch any disconnected channels since it is not apparent how they are to be integrated into stream network measurements involving stream ordering.

Morphometric Measurement Techniques

All basin and stream network morphometric variables can be determined from measurements with linear or areal dimensions. Linear attributes of the basin and stream network have been traditionally measured with a hand-held map measure, a process which requires several trials to reduce observer error. Areal measurements involve planimetry, either with a dot grid or a hand-operated device which integrates the area circumscribed by the traced perimeter. Again, repetitive measurement is required to eliminate observer error.

Increased accuracy and speed has now been achieved in morphometric measurement through the use of a sonic digitizer, such as the model owned by the Department of Geography at Oregon State University. The sonic digitizer uses a grid sensor of point or line data taken from the map and displays linear or areal measurements to 10^{-3} inches or square inches. Seventy-two morphometric variables were measured or calculated for fifteen watersheds in approximately one-third of the time normally required using traditional measurement techniques.

Statistical Methods

The intent of the present study is to establish the interrelation of morphometric variables with mean annual runoff, base flow, mean annual peak flow, and mean annual sediment yield. Strahler (1954) has distinguished between two types of variable association, regression and correlation. Regression involves the association of two or more variables when one is clearly the cause of the other. Independent and dependent variables cannot be identified among the morphometric, streamflow, and sediment data because they are considered to vary together. Indeed, the morphometric variables are considered to be indices of streamflow and sediment yield. Instead of a cause and effect relationship, the morphometric variable and either streamflow or sediment yield are the result of common causes, including lithology and the magnitude and frequency of climatic events.

All statistical inferences about the data must be based on a particular frequency distribution. The standard normal distribution approximates the distribution of a large number of data sets, but many authors claim that hydrologic data do not conform to this distribution. However, the logarithm of each data point often follows the normal distribution, a distribution termed log-normal. All data sets in the present study are approximately normally distributed as evidenced by a near-straight line of values for each variable tested when cumulative frequency is plotted on probability paper.

It is also imperative that the range of values for variables tested be wide enough to avoid excessive extrapolation.

In correlation studies, two regression lines of best fit can be derived by the method of least squares. For the purposes of this study, only one regression line was drawn, treating the morphometric variable as the independent (X) variable. The overall efficiency of the correlation is measured by the coefficient of determination (r^2), calculated as follows:

$$r^2 = \frac{SP^2}{(SS_x) \times (SS_y)}, \text{ where}$$

SS_x is sum of squares of deviations from the mean value of x, SS_y is sum of squares of deviations from the mean value of y, and SP is the sum of the products of deviations from the mean value of x times deviations from the mean value of y.

An r^2 value of .582 would indicate that 58.2 percent of the variance in streamflow or sediment yield is explained by the selected morphometric variable. A high r^2 value is not necessarily a good indicator of the quality of the predicting equation. The significance of the correlation can be tested by accounting for the degree of scatter, the slope of the

regression line, and the number of points used to determine the line. The test statistic is:

$$t^* = \frac{r(n - m)^{1/2}}{(1 - r^2)^{1/2}}$$, where

n = number of paired variables and m is the number of degrees of freedom lost (m = 2 for all correlations in the present study). Correlations were tested for significance at the .10 level. This means that a significant correlation has a probability of no more than ten percent of occuring by happenstance. A highly significant correlation has a probability of no more than five percent of occuring by chance.

Multiple correlation between morphometric variables and streamflow and sediment yield was not attempted, largely because hydrologic data may not conform to the premises upon which multiple regression analysis is based (Sharp et al., 1960):

1) There are no errors in the independent variables (errors occur only with the dependent variables);
2) the variance of the dependent variable does not change with changing levels of the independent variable; and
3) the observed values of the dependent variable are uncorrelated random events.

Sharp et al. conclude that,

> although the multiple [correlation] approach will result in a line of best fit and best estimating equation for hydrologic data, it is not safe to place too much reliance on values estimated by such equations, particularly at levels far removed from the mean, despite very high correlation coefficients.

Snyder (1962) and Mather and Doornkamp (1970) proposed alternative techniques of multivariate analysis for use where multiple correlation fails for hydrologic data, including factor analysis, cluster analysis, and multiple discriminant analysis.

DESCRIPTION OF THE STUDY AREAS

Five sets of grouped watersheds were selected for study areas based on the availability of streamflow and sediment data, topographic maps, and a documented history of land use activities. The total of fifteen basins represent a variety of lithologic and climatic settings (Figure 2).

H.J. Andrews Experimental Forest

The H.J. Andrews Experimental Forest lies in the Willamette National Forest in the western Cascades of Oregon. The area is drained by Lookout Creek, a tributary to the Blue River which drains, in turn, into the McKenzie River. The eight, small, instrumented watersheds are underlain by Cenozoic welded tuff and breccia, receive an average of about 75 inches of precipitation annually, and support a coniferous forest cover.

Watersheds 1, 2, and 3 comprise one set of grouped basins (Figure 3). Logging began in watershed 1 during August 1962, with 100 percent clear-cut by October 1966, followed by broadcast burning. Watershed 2 is the unlogged control basin. Roads were built in watershed 3 between April and October 1958, with 25 percent of the basin patch cut by February 1963, followed again by broadcast burning.

Watersheds 6, 7, and 8 comprise a second set of grouped basins (Figure 4). Roads were built and logging undertaken in watershed 6 during the summer of 1974, with slash burned in the following spring. Sixty percent of watershed 7 was shelterwood cut in summer, 1974, followed again by slash burning. Watershed 8 is the unlogged control basin.

Watersheds 9 and 10 comprise the third set of grouped basins (Figure 4). Watershed 9 is the unlogged control basin. Watershed 10 was clearcut during the spring and summer of 1975.

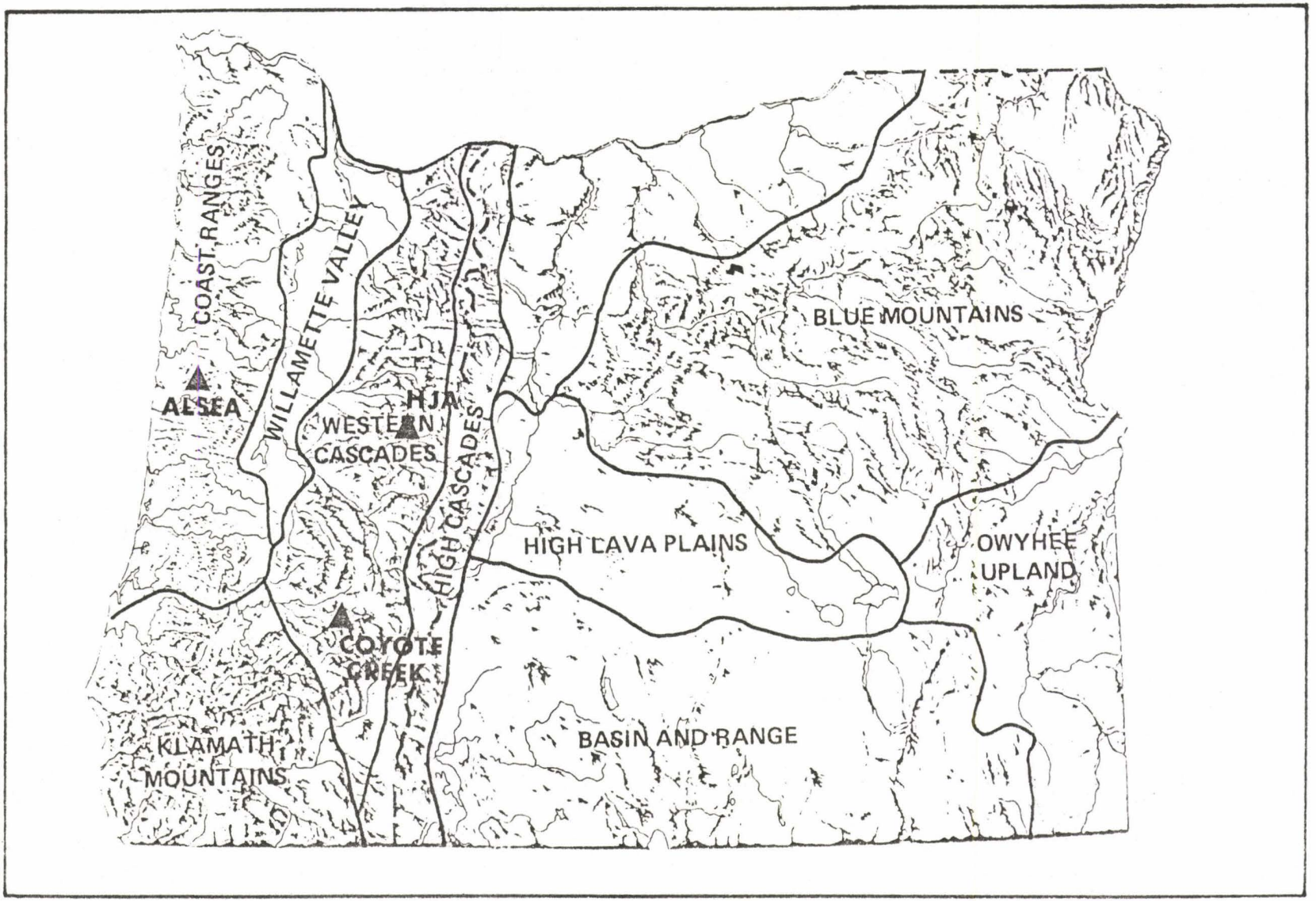

Figure 2. Location of study watersheds relative to physiographic regions in Oregon.

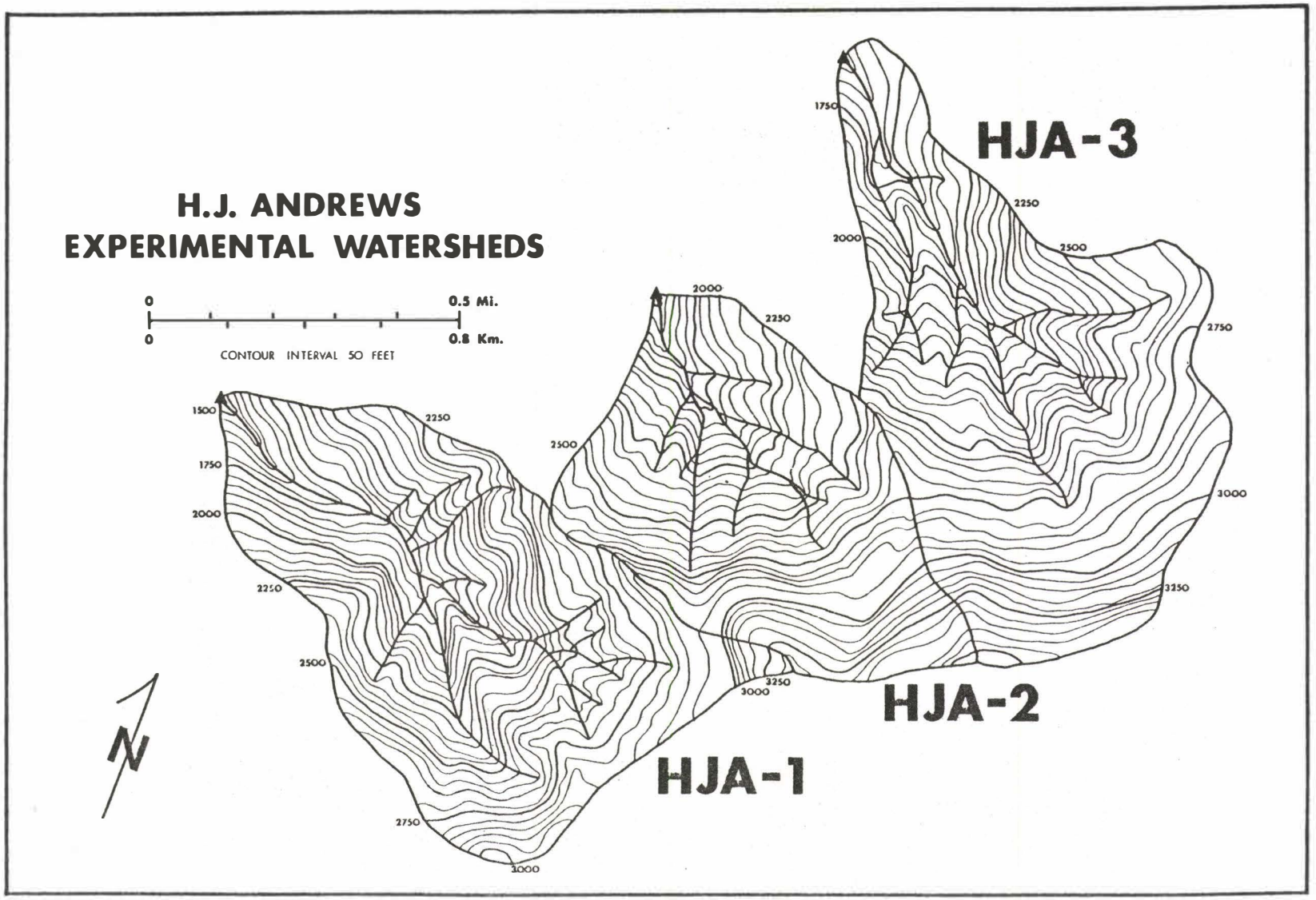

Figure 3. Topography and drainage network for watersheds 1, 2, and 3, H. J. Andrews Experimental Forest.

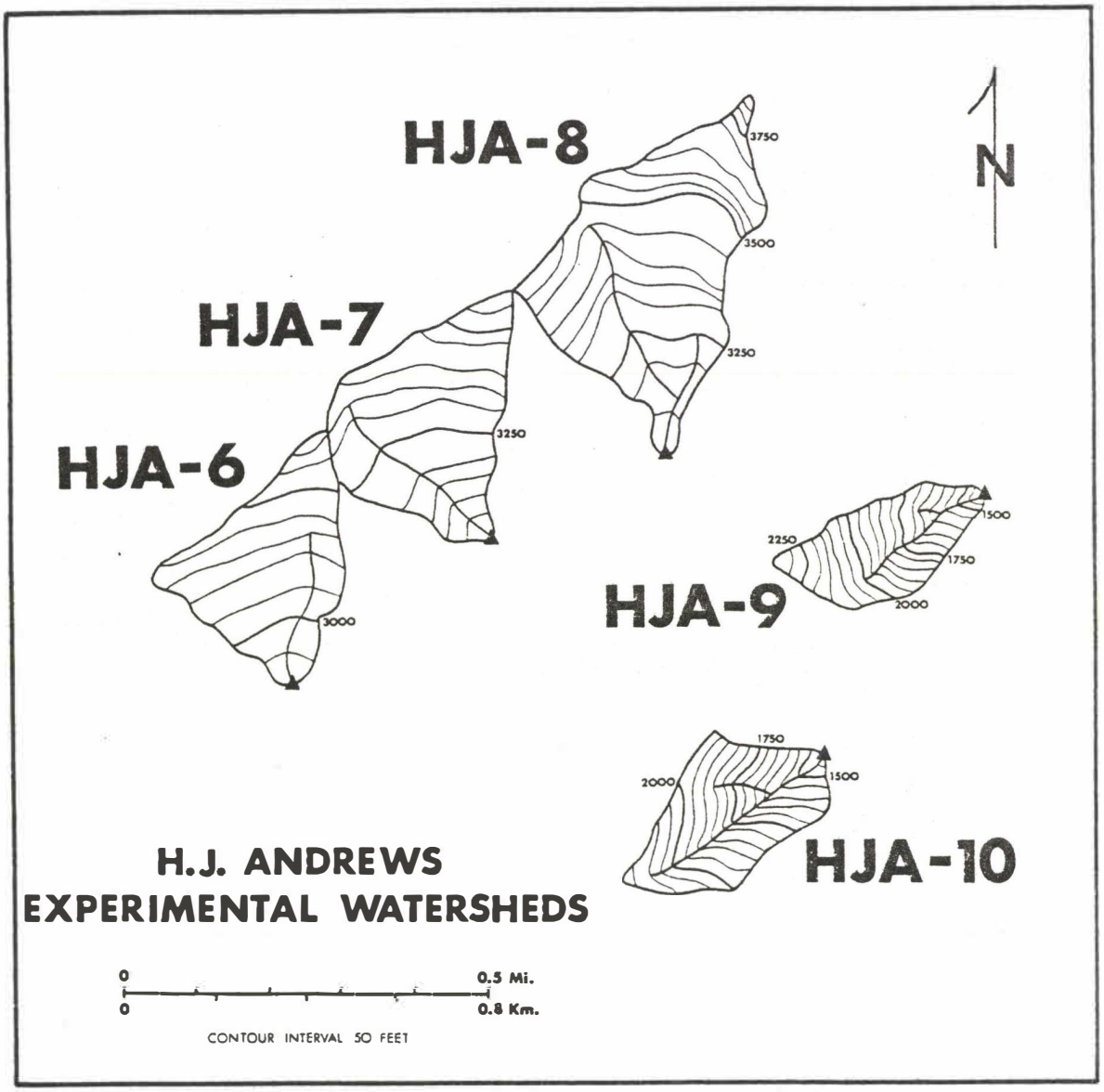

Figure 4. Topography and drainage network for watersheds 6, 7, and 8 and watersheds 9 and 10, H. J. Andrews Experimental Forest. Watersheds 9 and 10 are not shown in correct position relative to each other or to watersheds 6, 7 and 8.

Alsea Experimental Watersheds

The Alsea Experimental Watersheds lie on land owned by the Georgia-Pacific Corporation and the U.S. Forest Service (Siuslaw National Forest) within the Drift Creek drainage of the Oregon Coast Range. The area is underlain by marine sandstone and mudstone of the Tyee Formation, supports a mixed forest of Douglas-fir and red alder, and receives an average of 96 inches of precipitation annually.

Flynn Creek is the unlogged control basin (Figure 5). Logging began in the Deer Creek watershed in 1966, culminating in 25 percent of the basin clearcut in three patches (Figure 6). Slash was very lightly burned in each patch cut. Needle Branch was 82 percent clearcut in 1966 followed by a severe burn (Figure 7).

Coyote Creek Experimental Watersheds

The Coyote Creek Experimental Watersheds lie in the Umpqua National Forest in the western Cascades of Oregon (Figure 8). The area is underlain by Cenozoic non-welded tuff, supports a forest cover of mature sugar pine and Douglas-fir, and receives an average of about 40 inches of precipitation annually. Roads were built in watersheds 1, 2, and 3 in summer, 1970. Thirty percent of the timber was logged in watershed 1 between May and September, 1971 by shelterwood cuts. Thirty percent of the timber was also logged in watershed 2 during the same time period but in small clearcuts. Watershed 3 was entirely clearcut and watershed 4 is the unlogged control basin.

DESCRIPTION OF MORPHOMETRIC VARIABLES

Seventy-two basin and stream network morphometric variables were measured for each of the fifteen study basins. The derivation, units, and reference for each variable are tabulated by alphabetical order (Table I). The actual values are tabulated to three significant figures (Tables II-IV).

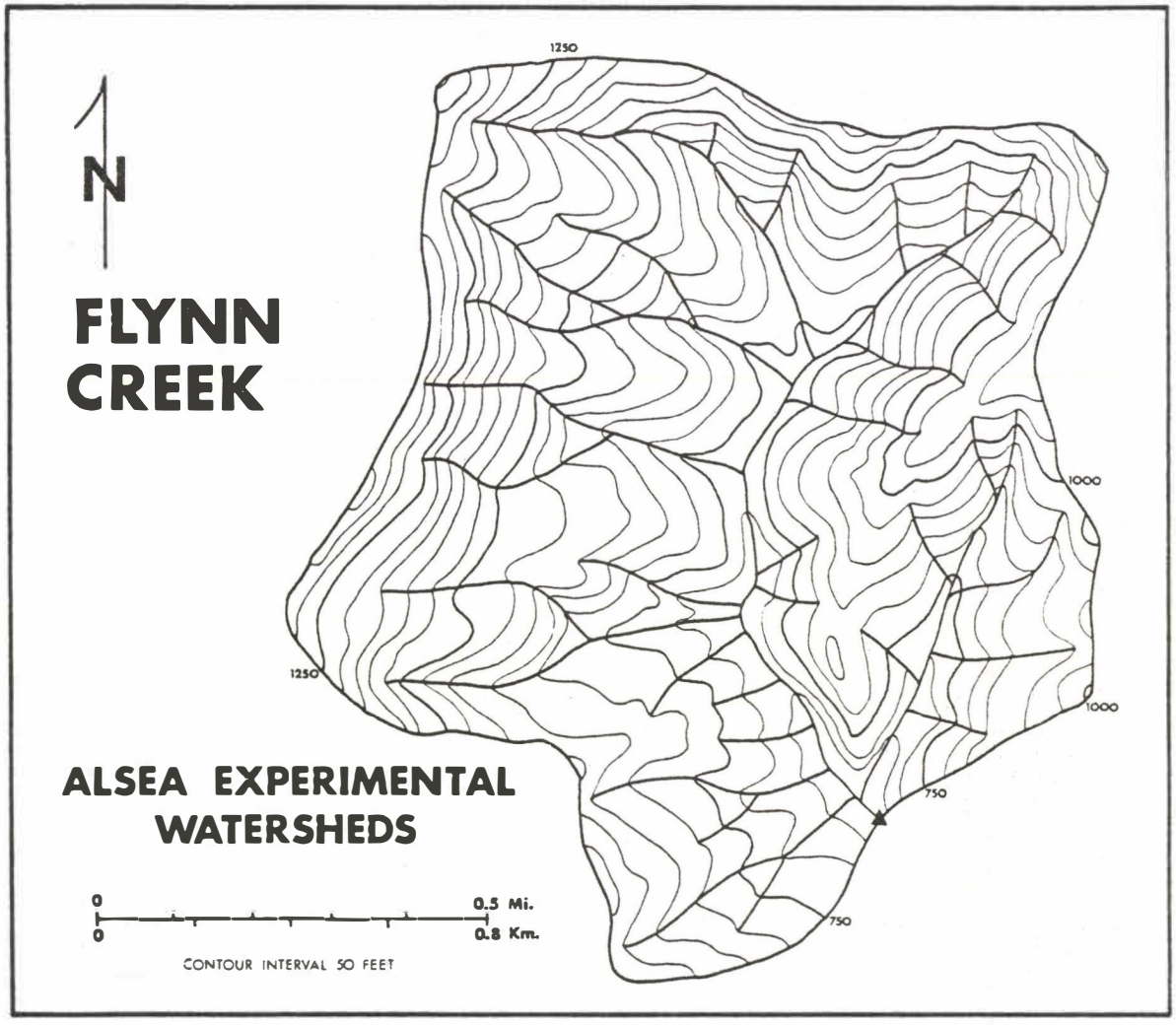

Figure 5. Topography and drainage network for Flynn Creek, Alsea Experimental Watersheds.

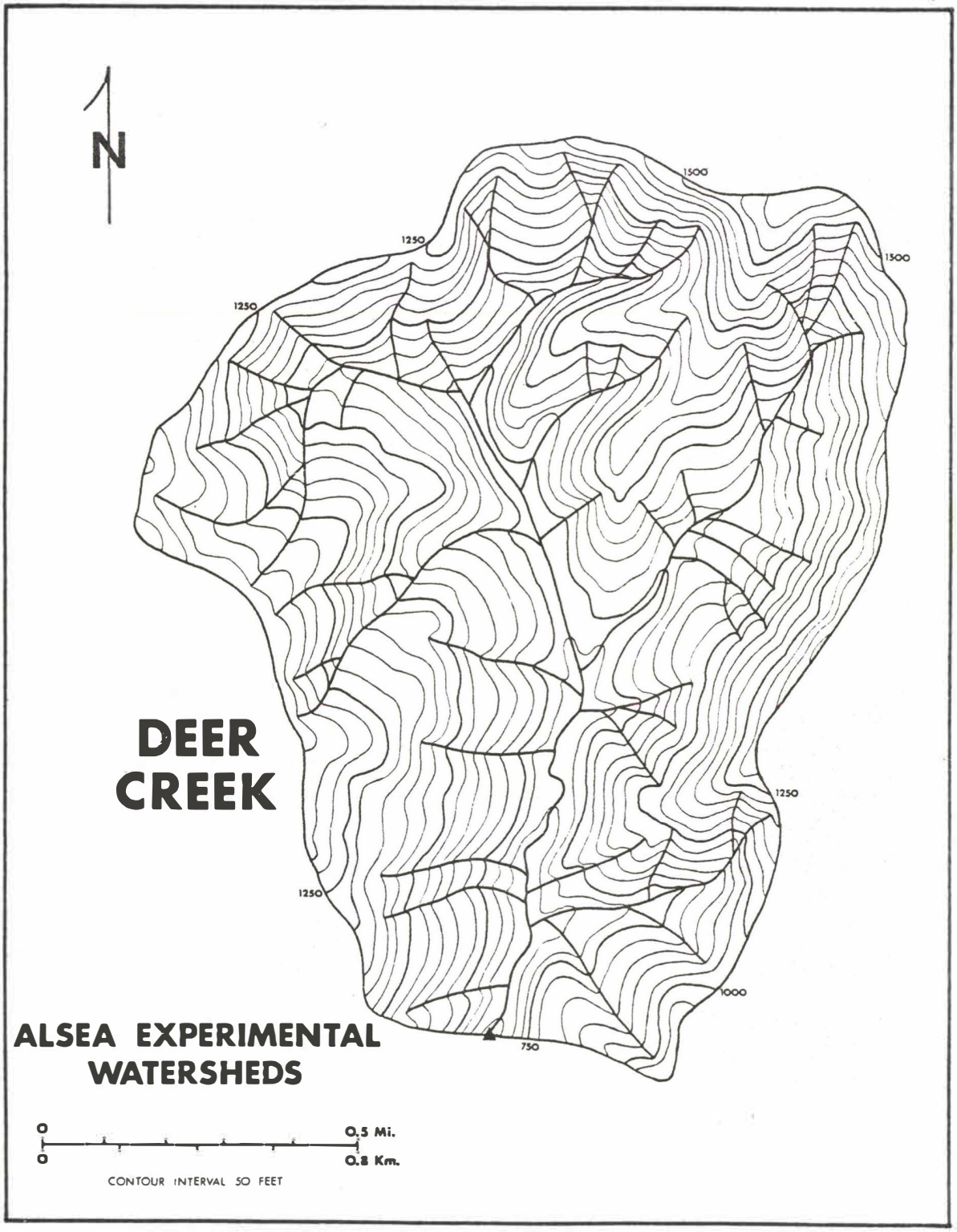

Figure 6. Topography and drainage network for Deer Creek, Alsea Experimental Watersheds.

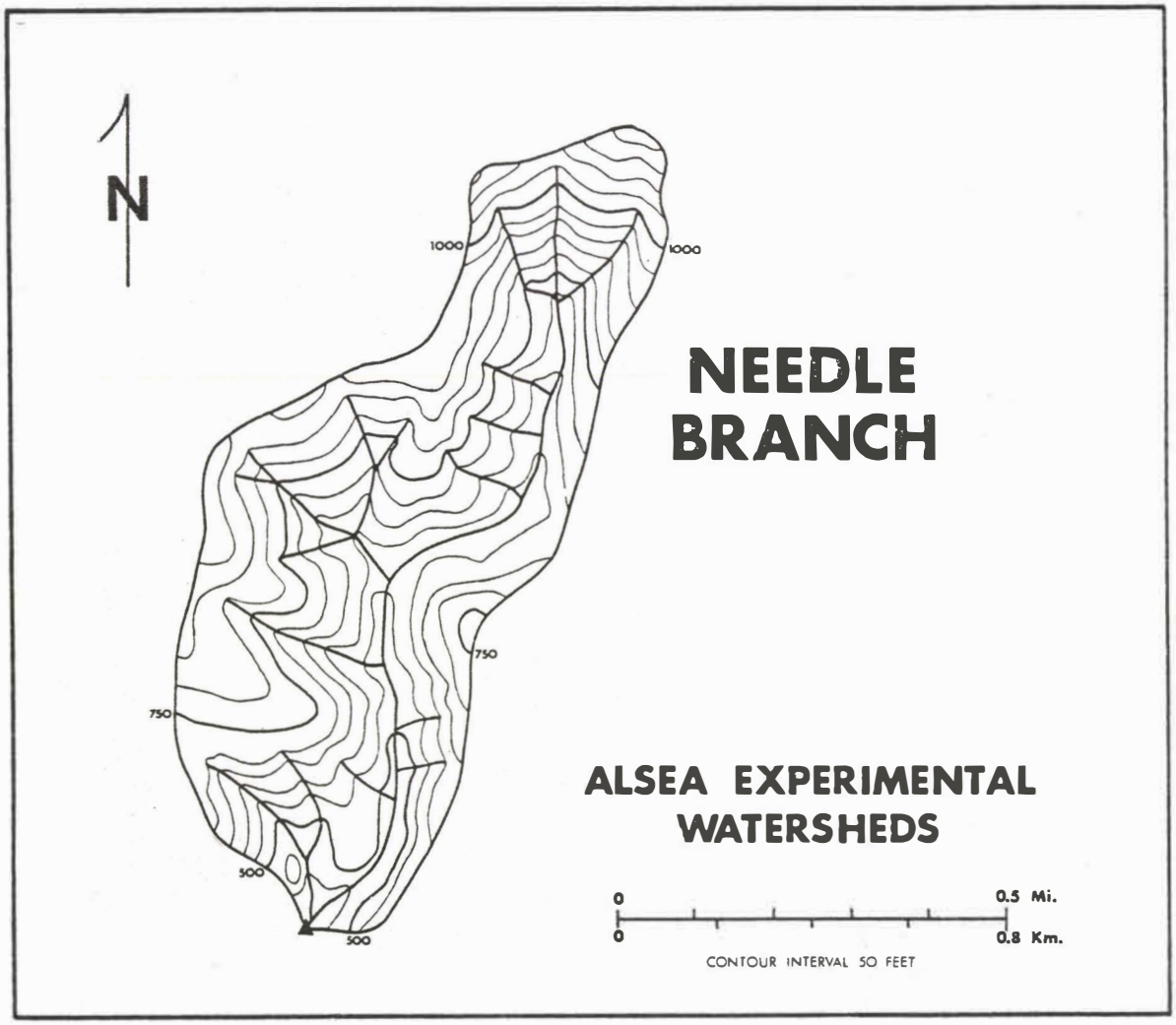

Figure 7. Topography and drainage network for Needle Branch, Alsea Experimental Watersheds.

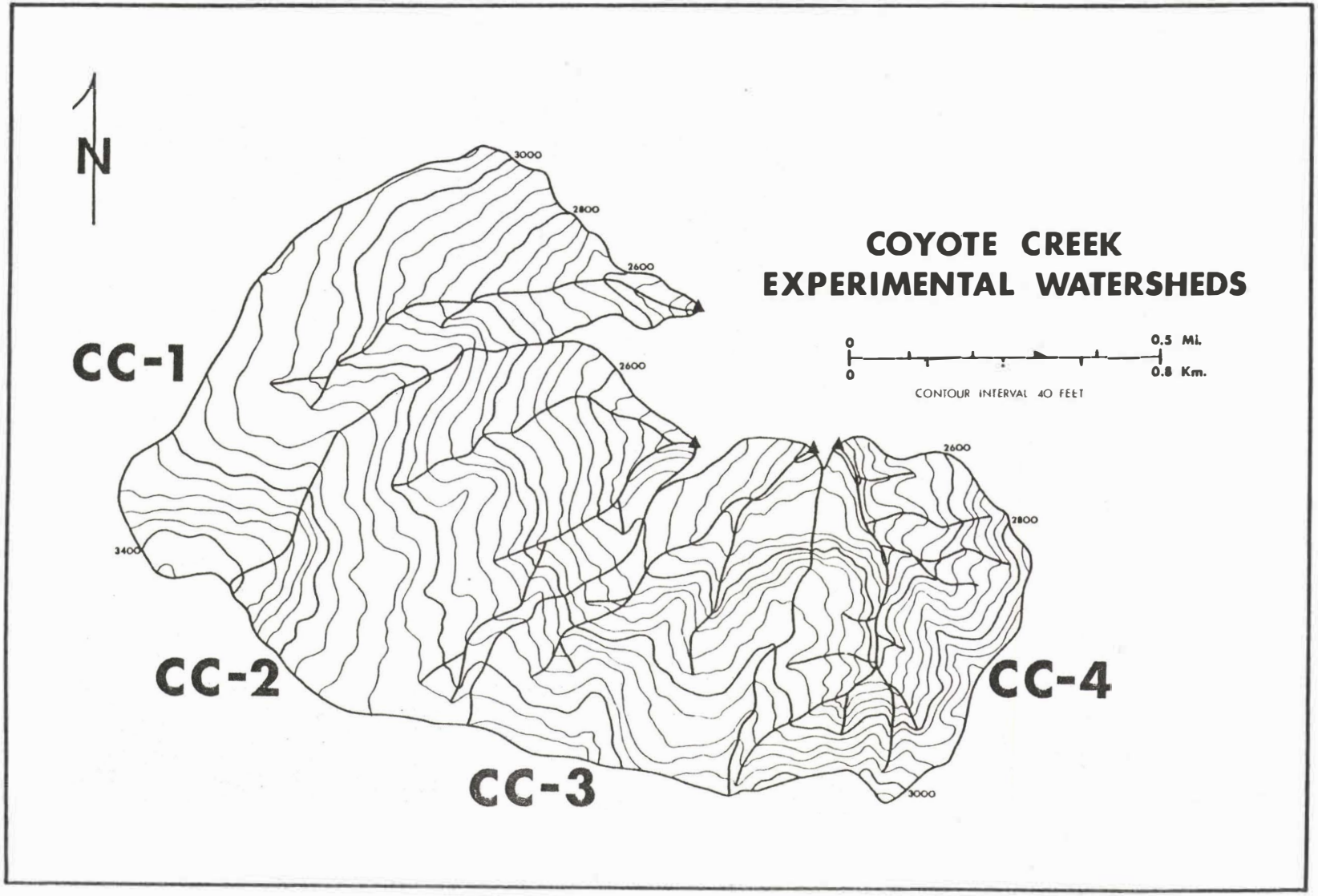

Figure 8. Topography and drainage network for watersheds 1, 2, 3, and 4, Coyote Creek Experimental Watersheds.

The basin morphometric variables can be grouped depending on whether they constitute areal, length, shape, or relief measurements. Area has been termed the "devil's own variable" by Anderson (1957) because it correlates with many other morphometric variables. Strahler (1957) claims that area is the prime determinant of total runoff or sediment yield. It was therefore decided to normalize all streamflow and sediment data on an area-yield basis. The derived correlations between morphometric variables and streamflow or sediment yield will have a greater applicability for land management purposes.

Basin linear measurements include perimeter (P), basin length (BL), basin width (BW), and length to basin center (LBC). The latter three are derived by connecting the basin mouth with a point on the mainstream where a line perpendicular to the first line divides the basin into two sections of equal area. Extending the line from the mouth through this point to the basin boundary will define the basin length. The line perpendicular to basin length at the basin center defines the basin width. The length to the center of the basin is measured as the length along the mainstream from the mouth to the point where the line divides the basin into two sections of equal area. These measurement criteria are less arbitrary than other criteria, particularly for basin length. The technique described above is accurate and minimizes observer bias. An alternate measurement of basin length was proposed by Strahler (1957) who defined length as the longest dimension of the basin. Horton (1932) defined basin length as the distance from the mouth to a part of the basin boundary opposite the head of the mainstream. Schumm (1954) defined basin length as the longest dimension of the basin parallel to the mainstream.

There are several indices of basin shape, including circularity (C), basin elongation (BE), form factor-1 (FF1), form factor-2 (FF2), compactness coefficient (CC), and lemniscate (l). All shape measurements are independent of basin area. DeWiest (1965) and Strahler (1964) have shown how basin shape affects the shape of the storm hydrograph. Storm period runoff in a circular basin will tend to reach the mouth

TABLE I. BASIN, STREAM NETWORK, AND NETWORK-BASIN MORPHOMETRIC VARIABLES WITH DERIVATION AS USED IN PRESENT STUDY.

SYMBOL	VARIABLE	DERIVATION	UNITS	REFERENCE
A	Area	Direct measure	$Mi.^2$	Horton, 1945
A1	Area 1st Order Basins	Direct measure	$Mi.^2$	Schumm, 1956
A2	Area 2nd Order Basins	Direct measure	$Mi.^2$	Schumm, 1956
A3	Area 3rd Order Basins	Direct measure	$Mi.^2$	Schumm, 1956
A4	Area 4th Order Basins	Direct measure	$Mi.^2$	Schumm, 1956
B	Bifurcation Ratio	B = antilog of slope of regression of U vs log NU	--	Strahler, 1957
BAR	Basin Area Ratio	BAR = antilog of slope of regression of U vs log MAU	--	Schumm, 1956
BE	Basin Elongation	BE = diameter of circle with same area as basin/BL, $BE = [2 \times (A/3.14)^{1/2}]/BL$	--	Schumm, 1956
BL	Basin Length	Direct measure of line extended from LBC to basin perimeter	Mi.	Potter, 1961
BR	Basin Relief	BR = relief along BL	Ft.	Schumm, 1956
BW	Basin Width	Direct measure of basin axis perpendicular to BL at basin center	Mi.	Schumm, 1956
C	Circularity	C = A/area of circle with same P, $C = (4 \times 3.14 \times A)/P^2$	--	Miller, 1953
CC	Compactness Coefficient	CC = P/circumference of circle with same A, $CC = P/[2 \times (3.14 \times A)^{1/2}]$	--	Rothacher, et al, 1967
CCM	Constant of Channel Maintenance	CCM = 1/DD	$Mi.^2/Mi.$	Schumm, 1956
DD	Drainage Density	$DD = TSL/A_2$	$Mi./Mi.^2$	Horton, 1945
FF1	Form Factor - 1	$FF1 = A/BL^2$	--	Horton, 1932
FF2	Form Factor - 2	FF2 = BL/BW	--	Horton, 1932

TABLE I. Continued

SYMBOL	VARIABLE	DERIVATION	UNITS	REFERENCE
L	Lemniscate	$K = BL^2/(4 \times A)$	--	Chorley, et al, 1957
L1	Length 1st Order Streams	Direct measure	Mi.	Horton, 1945
L2	Length 2nd Order Streams	Direct measure	Mi.	Horton, 1945
L3	Length 3rd Order Streams	Direct measure	Mi.	Horton, 1945
L4	Length 4th Order Streams	Direct measure	Mi.	Horton, 1945
LBC	Length to Basin Center	Direct measure of length along mainstream to point where line divides basin into two sections of equal area	Mi.	Chorley, 1969
LOF	Length of Overland Flow	LOF = 5280/(2 x DD)	Ft.	Horton, 1945
MA1	Mean Area 1st Order Basins	MA1 = A1/N1	$Mi.^2$	Schumm, 1956
MA2	Mean Area 2nd Order Basins	MA2 = A2/N2	$Mi.^2$	Schumm, 1956
MA3	Mean Area 3rd Order Basins	MA3 = A3/N3	$Mi.^2$	Schumm, 1956
MA4	Mean Area 4th Order Basins	MA4 = A4/N4	$Mi.^2$	Schumm, 1956
MBR	Maximum Basin Relief	MBR = XE - NE	Ft.	Schumm, 1956
ME	Mean Elevation	ME = (NE + XE)/2	Ft.	Thomas and Benson, 1970
ML	Mainstream Length	Direct measure	Mi.	Taylor and Schwarz, 1952
ML1	Mean Length 1st Order Streams	ML1 = L1/N1	Mi.	Horton, 1945
ML2	Mean Length 2nd Order Streams	ML2 = L2/N2	Mi.	Horton, 1945
ML3	Mean Length 3rd Order Streams	ML3 = L3/N3	Mi.	Horton, 1945
ML4	Mean Length 4th Order Streams	ML4 = L4/N4	Mi.	Horton, 1945
MR	Mainstream Relief	Direct measure	Ft.	Taylor and Schwarz, 1952
MR1	Mean Relief 1st Order Streams	MR1 = R1/N1	Ft.	Horton, 1945
MR2	Mean Relief 2nd Order Streams	MR2 = R2/N2	Ft.	Horton, 1945

TABLE I. Continued

SYMBOL	VARIABLE	DERIVATION	UNITS	REFERENCE
MR3	Mean Relief 3rd Order Streams	MR3 = R3/N3	Ft.	Horton, 1945
MR4	Mean Relief 4th Order Streams	MR4 = R4/N4	Ft.	Horton, 1945
MS	Mainstream Slope	MS = MR/ML	Ft./Mi.	Taylor and Schwarz, 1952
MS1	Mean Slope 1st Order Streams	MS1 = MR1/ML1	Ft./Mi.	Horton, 1945
MS2	Mean Slope 2nd Order Streams	MS2 = MR2/ML2	Ft./Mi.	Horton, 1945
MS3	Mean Slope 3rd Order Streams	MS3 = MR3/ML3	Ft./Mi.	Horton, 1945
MS4	Mean Slope 4th Order Streams	MS4 = MR4/ML4	Ft./Mi.	Horton, 1945
MU	Mainstream Order	See notes for symbol "U"	Enumerative	Strahler, 1957
N	Maximum No. of Crenulations	Direct count of crenulations for contour with most crenulations	Enumerative	Strahler, 1957
N1	Number of 1st Order Streams	Direct count	Enumerative	Strahler, 1957
N2	Number of 2nd Order Streams	Direct count	Enumerative	Strahler, 1957
N3	Number of 3rd Order Streams	Direct count	Enumerative	Strahler, 1957
N4	Number of 4th Order Streams	Direct count	Enumerative	Strahler, 1957
NE	Minimum Elevation	Direct measure	Ft.	Schumm, 1956
P	Perimeter	Direct measure	Mi.	Smith, 1950
R1	Relief of 1st Order Streams	Direct measure	Ft.	Horton, 1945
R2	Relief of 2nd Order Streams	Direct measure	Ft.	Horton, 1945
R3	Relief of 3rd Order Streams	Direct measure	Ft.	Horton, 1945
R4	Relief of 4th Order Streams	Direct measure	Ft.	Horton, 1945
RD	Relative Density	$RD = SF/DD^2$	--	Melton, 1958
RER	Relative Relief	R = BR/(5280 x P)	--	Strahler, 1964
RN	Ruggedness Number	RN = (BR/5280) x DD	--	Melton, 1958
RR	Relief Ratio	RR = BR/(5280 x BL)	--	Schumm, 1956
SF	Stream Frequency	SF = TNS/A	$No./Mi.^2$	Horton, 1945
SLB	Ratio of SLR to B	SLB = SLR/B	--	Horton, 1945
SLR	Stream Length Ratio	SLR = antilog of slope of regression of U vs log MLU	--	Horton, 1945

TABLE I. Continued

SYMBOL	VARIABLE	DERIVATION	UNITS	REFERENCE
SRR	Stream Relief Ratio	SRR = antilog of slope of regression of U vs log MRU	--	Horton, 1945
SSR	Stream Slope Ratio	SSR = antilog of slope of regression of U vs log MSU	--	Horton, 1945
TE1	Transport Efficiency Factor - 1	TE1 = B x TSL	--	Lustig, 1965
TE2	Transport Efficiency Factor - 2	TE2 = TNS x SSR	--	Lustig, 1965
TNS	Total Number of Streams	Direct count	Enumerative	Horton, 1945
TR	Texture Ratio	TR = N/P	--	Strahler, 1957
TSL	Total Stream Length	Direct measure, TSL = L1 + L2 + L3 + L4	Mi.	Horton, 1945
TSP	Texture-Slope Product	TSP = DD x RR	--	Schumm, 1969
U	Stream Order	Unbranched stream + branched stream = 2nd order; 2nd order + 2nd order = 3rd order; etc.	Enumerative	Strahler, 1957
XE	Maximum Elevation	Direct measure	Ft.	Schumm, 1956

simultaneously from all portions of the watershed. Storm period runoff in an elongated basin would be distributed in a manner resulting in lower peak flows. Storm period sediment yield can be expected to vary with basin shape in a similar fashion.

Relief measurements of the basin include maximum elevation (XE), minimum elevation (NE), mean elevation (ME), maximum basin elevation (MBE), basin relief (BR), relief ratio (RR), and relative relief (RER). Basin relief is measured as the difference in elevation along the line defining basin length described earlier. Relief ratio is independent of area and has a physical basis for use in correlation studies since it measures overall basin steepness. Basins with a high relief ratio would experience quick delivery of storm runoff, have a high potential for erosional energy, and tend to discourage high base flows by increasing the hydraulic gradient and thereby accelerating delivery of groundwater to streams (Strahler, 1964).

The most fundamental morphometric measurement of the stream network is stream order which is generally used to index streamflow or channel size. Horton (1945) described an ordering system with two unbranched tributaries joining to form a second order stream; two second order streams join to form a third order stream and so on, with the mainstream designated the highest order from the mouth to the headwaters. Strahler (1957) adopted Horton's technique except for the mainstream designation, a system now in wide use. However, Strahler's method does not account for the streamflow increases due to junctions of lower order streams with higher order streams, as in the case of a first order tributary to a fifth order stream. Shreve (1966) proposed a segment ordering system which sums the magnitude of all tributary segments. Graf (1975) sought to further improve ordering by accounting for streamflow source areas draining directly into the mainstream. Graf's cumulative ordering system is modified from Shreve's method, with stream order determined from the number of upstream segments plus one. Finally, Schneidegger (1965) created a system to account for the effect of tributaries of unequal order, but is somewhat more complicated. By convention, the Strahler system is employed in the present study.

TABLE II. VALUES FOR BASIN MORPHOMETRIC VARIABLES.

SYMBOL	UNITS	HJA-1	HJA-2	HJA-3	HJA-6	HJA-7	HJA-8	HJA-9	HJA-10	Flynn Cr.	Deer Cr.	Needle Br.	CC-1	CC-2	CC-3	CC-4
A	$Mi.^2$	.370	.233	.391	.050	.059	.083	.033	.039	.785	1.17	.274	.267	.264	.192	.188
A1	$Mi.^2$	.230	.190	.270	.050	.059	.071	.022	.031	.621	.860	.221	.101	.240	.110	.121
A2	$Mi.^2$	.160	.181	.370	--	--	.083	.033	.039	.712	.750	.232	.267	.264	.161	.091
A3	$Mi.^2$	.370	.233	.391	--	--	--	--	--	.785	.790	.274	--	--	.192	.188
A4	$Mi.^2$	--	--	--	--	--	--	--	--	--	1.17	--	--	--	--	--
MA1	$Mi.^2$	.018	.024	.030	.050	.059	.036	.011	.016	.018	.018	.013	.034	.040	.022	.011
MA2	$Mi.^2$	.053	.091	.185	--	--	.083	.033	.039	.089	.075	.058	.267	.264	.081	.030
MA3	$Mi.^2$	.370	.233	.391	--	--	--	--	--	.785	.395	.274	--	--	.192	.188
MA4	$Mi.^2$	--	--	--	--	--	--	--	--	--	1.17	--	--	--	--	--
BAR	--	.221	.295	.275	--	--	.434	.333	.410	.160	.252	.192	.127	.152	.395	.230
P	Mi.	2.69	2.01	2.88	.950	.970	1.31	.700	.790	3.49	4.45	2.70	2.54	2.09	1.82	1.75
BL	Mi.	.900	.730	1.04	.320	.290	.390	.260	.320	1.08	1.45	1.05	.810	.650	.680	.550
BW	Mi.	.480	.460	.570	.240	.320	.310	.140	.160	1.02	1.11	.430	.340	.410	.330	.430
LBC	Mi.	.530	.370	.610	.150	.160	.280	.150	.150	.520	.770	.550	.590	.380	.360	.300
C	--	.642	.724	.592	.696	.788	.607	.846	.785	.809	.742	.472	.520	.759	.728	.771
BE	--	.763	.746	.679	.789	.945	.834	.789	.697	.926	.842	.563	.720	.892	.727	.890
FF1	--	.457	.437	.362	.488	.702	.546	.488	.381	.673	.556	.249	.407	.625	.415	.621
FF2	--	1.88	1.59	1.82	1.33	.906	1.26	1.86	2.00	1.06	1.31	2.44	2.38	1.59	2.06	1.28
CC	--	1.25	1.17	1.30	1.20	1.13	1.28	1.09	1.13	1.11	1.16	1.46	1.39	1.15	1.17	1.14
L	--	.547	.572	.692	.512	.356	.458	.512	.656	.371	.449	1.01	.614	.400	.602	.402
XE	Ft.	3325	3500	3550	3375	3575	3875	2375	2175	1475	1625	1225	3460	3420	3100	3020
NE	Ft.	1450	1725	1575	2900	3000	3000	1375	1425	600	575	425	2460	2460	2340	2340
ME	Ft.	2390	2615	2565	3140	3290	3440	1875	1800	1040	1100	825	2960	2940	2720	2680
MBR	Ft.	1875	1775	1975	475	575	875	1000	750	875	1050	800	1000	960	760	680
BR	Ft.	1425	1650	1800	400	375	550	800	725	600	850	650	680	600	740	640
RR	--	.300	.428	.328	.237	.245	.267	.583	.429	.105	.111	.117	.159	.175	.206	.220
RER	--	.100	.155	.118	.080	.073	.080	.216	.174	.033	.036	.046	.051	.054	.077	.069

TABLE III. VALUES FOR STREAM NETWORK MORPHOMETRIC VARIABLES.

SYMBOL	UNITS	HJA-1	HJA-2	HJA-3	HJA-6	HJA-7	HJA-8	HJA-9	HJA-10	Flynn Cr.	Deer Cr.	Needle Br.	CC-1	CC-2	CC-3	CC-4
MU	Enumerative	3	3	3	1	1	2	2	2	3	4	3	2	2	3	3
TNS	Enumerative	17	11	12	1	1	3	3	3	43	60	22	4	7	8	15
N1	Enumerative	13	8	9	1	1	2	2	2	34	47	17	3	6	5	11
N2	Enumerative	3	2	2	--	--	1	1	1	8	10	4	1	1	2	3
N3	Enumerative	1	1	1	--	--	--	--	--	1	2	1	--	--	1	1
N4	Enumerative	--	--	--	--	--	--	--	--	--	1	--	--	--	--	--
B	--	3.61	2.83	3.00	--	--	2.00	2.00	2.00	5.83	3.73	4.12	3.00	6.00	2.23	3.32
ML	Mi.	.890	.510	.810	.210	.270	.350	.200	.290	1.31	2.89	1.51	.750	.610	.610	.670
TSL	Mi.	2.39	1.56	2.19	.210	.270	.440	.240	.370	8.09	10.5	3.21	.870	1.38	1.14	1.94
L1	Mi.	1.53	1.04	1.22	.210	.270	.360	.170	.280	5.57	6.84	1.95	.222	.860	.440	1.28
L2	Mi.	.170	.350	.840	--	--	.080	.070	.090	1.82	2.07	.760	.650	.520	.580	.290
L3	Mi.	.690	.170	.130	--	--	--	--	--	.700	.950	.500	--	--	.120	.137
L4	Mi.	--	--	--	--	--	--	--	--	--	.650	--	--	--	--	--
ML1	Mi.	.118	.083	.136	.210	.270	.180	.085	.140	.164	.146	.115	.074	.143	.088	.116
ML2	Mi.	.006	.175	.420	--	--	.080	.070	.090	.228	.207	.190	.650	.520	.290	.097
ML3	Mi.	.690	.170	.130	--	--	--	--	--	.700	.475	.500	--	--	.120	.137
ML4	Mi.	--	--	--	--	--	--	--	--	--	.650	--	--	--	--	--
SLR	--	.414	.699	1.02	--	--	2.25	1.21	1.56	.484	.588	.480	.114	.275	.856	.920
MR	Ft.	1350	975	1175	250	350	350	625	675	700	875	625	620	580	620	620
R1	Ft.	3775	2650	2875	250	350	350	500	800	7625	13050	3225	250	1150	550	2500
R2	Ft.	625	600	750	--	--	75	200	150	950	2100	470	725	25	750	300
R3	Ft.	900	225	100	--	--	--	--	--	125	300	150	--	--	75	275
R4	Ft.	--	--	--	--	--	--	--	--	--	100	--	--	--	--	--
MR1	Ft.	290	331	319	250	350	175	250	400	224	278	190	83	192	110	227
MR2	Ft.	208	300	375	--	--	75	200	150	119	210	117	725	25	375	100
MR3	Ft.	900	225	100	--	--	--	--	--	125	150	150	--	--	75	275
MR4	Ft.	--	--	--	--	--	--	--	--	--	100	--	--	--	--	--

TABLE III. Continued

SYMBOL	UNITS	HJA-1	HJA-2	HJA-3	HJA-6	HJA-7	HJA-8	HJA-9	HJA-10	Flynn Cr.	Deer Cr.	Needle Br.	CC-1	CC-2	CC-3	CC-4
SRR	--	.568	1.21	1.79	--	--	2.33	1.25	2.67	1.34	1.41	1.12	.114	7.68	.826	.909
MS	Ft./Mi.	1520	1910	1450	1190	1300	1000	3130	2330	530	300	410	830	950	1020	930
MS1	Ft./Mi.	2460	3990	2450	1190	1300	970	2940	2860	1370	1900	1650	1190	1340	1250	1960
MS2	Ft./Mi.	10420	1710	890	--	--	940	2860	1670	520	1010	620	1120	50	1290	1030
MS3	Ft./Mi.	1300	1320	770	--	--	--	--	--	180	320	300	--	--	630	2000
MS4	Ft./Mi.	--	--	--	--	--	--	--	--	--	150	--	--	--	--	--
SSR	--	1.37	1.67	1.73	--	--	1.04	1.04	1.71	2.77	2.40	2.33	1.00	27.9	.860	.988
TE1	--	8.60	4.41	6.57	--	--	.880	.480	.740	47.5	39.3	13.3	2.61	8.28	2.57	6.44
TE2	--	23.3	18.4	20.8	--	--	3.12	3.09	8.01	119	144	51.3	4.00	195	6.88	14.8
WTF	--	11.8	6.44	5.48	--	--	.924	1.61	2.19	35.7	12.4	21.3	27.9	598	2.95	7.10

TABLE IV. VALUES FOR MORPHOMETRIC VARIABLES WHICH RELATE THE STREAM NETWORK TO BASIN MORPHOLOGY.

SYMBOL	UNITS	HJA-1	HJA-2	HJA-3	HJA-6	HJA-7	HJA-8	HJA-9	HJA-10	Flynn Cr.	Deer Cr.	Needle Br.	CC-1	CC-2	CC-3	CC-4
SF	No./Mi.^{2}	45.9	47.2	30.7	20.0	16.9	36.1	90.9	76.9	54.8	51.3	80.3	15.0	26.5	41.7	79.8
DD	Mi./Mi.^{2}	6.46	6.70	5.60	4.20	4.58	5.30	7.27	9.49	10.3	8.97	11.7	3.26	5.23	5.94	10.3
RN	--	1.74	2.09	1.91	.318	.325	.552	1.10	1.30	1.17	1.44	1.44	.420	.594	.833	1.25
LOF	Ft.	409	394	471	629	576	498	363	278	256	294	225	810	505	444	256
CCM	Mi.^{2}/Mi.	.155	.149	.179	.238	.218	.189	.138	.105	.097	.111	.085	.307	.191	.168	.097
RD	--	1.10	1.05	.979	1.13	.806	1.29	1.72	.854	.517	.638	.585	1.41	.969	1.18	.752
TSP	--	1.94	2.87	1.84	.995	1.12	1.42	4.23	4.07	1.08	.996	1.37	.518	.915	1.22	2.27
N	Enumerative	8	7	7	1	1	2	2	2	26	33	12	2	3	4	9
TR	--	2.97	3.48	2.43	1.05	1.03	1.53	2.86	2.53	7.45	7.42	4.44	.787	1.44	2.20	5.14

Measurements of stream numbers, stream length, stream relief, and stream slope are used to generate ratios which are more useful in correlation studies with streamflow and sediment yield normalized on an area-yield basis. The two transport efficiency factors (TE1, TE2) were developed by Lustig (1965) to reflect potential energy available in the overall stream network to perform erosional work.

There are at least ten morphometric variables which relate the stream network to basin morphology (Table IV). Stream frequency, drainage density, and texture-slope product are of particular interest because they reflect how efficiently an area is drained. Each should vary directly with annual runoff, mean annual peak flow, and sediment yield while varing indirectly with base flow.

Several morphometric variables were not measured in the present study, including hypsometric integral, stream geometry number, and average land slope. Hypsometry is used by some authors to derive mean elevation by relating the horizontal cross sectional drainage basin area to elevation. The stream geometry number is computed by $(H \times DD)/S_g$, where H is the vertical drop from divide to adjacent channel, DD is drainage density, and S_g is the slope of the ground surface from divide to stream. Calculation of average land slope for basin involves random sampling procedures, a task beyond the scope of the present study.

LITERATURE REVIEW OF PREDICTIVE MODELING WITH MORPHOMETRIC VARIABLES

A wide range of technical literature supports the use of basin and stream network morphometric variables to estimate or predict streamflow and sediment yield. Most studies reviewed below undertook a multivariate analysis and many incorporated climatic or land cover factors. Mention is made below only of those studies which found useful relationships with morphometric variables.

Predictors of Mean Annual Runoff

A review of the literature revealed sixteen morphometric variables which have been used to estimate or predict mean annual runoff or a similar streamflow quantity such as water yield, instantanious discharge, mean discharge, rainfall-runoff ratios, and flow-duration data (Table V). One of the earliest morphometric studies was conducted by Barrows (1933) who used 44 gaging stations in the Connecticut River basin to derive a general relationship between mean annual runoff, area, and altitude. Blyth and Rodda (1973) related total active stream length to discharge in a small clay basin in southeast England. Burkham (1966) examined the relationship between area and mean annual runoff over a ten-year period for a 21.3 square mile area in New Mexico. Gregory and Walling (1973) cited the work of Chebotarev who found a correlation between drainage density and percent of swamped area to runoff per unit area in the U.S.S.R. Diaz et al, (1968) identified area and average land slope as the most important factors affecting water yield. Graf (1975) discovered a relationship between his cumulative stream ordering system and discharge. Glymph and Holton (1973) related basin area to mean annual runoff for areas in Ohio, Texas, and Arizona, each with a unique correlation. Gregory and Walling (1968) found that discharge is proportional to the square of drainage density, noting that active drainage density in a particular basin is not static. Hann and Allen (1972) compared two techniques of multivariate analysis to predict mean annual runoff using area, basin length, relief ratio, basin shape, stream frequency, and basin perimeter (r^2 = 0.97). A publication by Hack (1957) is often cited in which he presented a graphical correlation between mean discharge and drainage area for seven locations in the Piedmont and Coastal Provinces of the eastern U.S. Hadley and Schumm (1961) correlate relief ratio and drainage density with mean annual runoff for several locations in the Cheyenne River basin. Howe (1960) showed that total annual runoff from a basin is related to area and precipitation using the rational formula. Gregory and Walling (1973) reprinted a graphical relationship between drainage density and runoff intensity (cm/hr.), first published by Melton. Morisawa (1958) examined the usefulness of

TABLE V. MORPHOMETRIC VARIABLES USED TO ESTIMATE MEAN ANNUAL RUNOFF.

REFERENCE	Area	Drainage Density	Total Stream Length	Basin Length	Basin Relief	Relief Ratio	Mainstream Length	Basin Shape	Mainstream Slope	Mainstream Relief	Stream Order	Stream Frequency	Total Stream Number	Mean Elevation	Texture Slope Product	Basin Perimeter
Barrows, 1933	X													X		
Blyth & Rodda, 1973			X													
Burkham, 1966	X															
Chebotarev, 1973		X														
Diaz et. al., 1968	X															
Glymph & Holton, 1973	X															
Graf, 1975											X					
Gregory & Walling, 1968	*	X	*													
Haan & Allen, 1972	X			X	*	X		X				X	*			X
Hack, 1957	X															
Hadley & Schumm, 1961	*	X	*	*	*	X										
Howe, 1960	X															
Melton, 1973		X														
Morisawa, 1958	*	X	*	*				X								
Morisawa, 1962	X		X	*	*	X	*	X	X	*		X	*			
Morisawa, 1967							X									
Mustonen, 1967	X															
Rakhamanov & Babak, 1971	X						*		X	*				X		

TABLE V. Continued

REFERENCE	Area	Drainage Density	Total Stream Length	Basin Length	Basin Relief	Relief Ratio	Mainstream Length	Basin Shape	Mainstream Slope	Mainstream Relief	Stream Order	Stream Frequency	Total Stream Number	Mean Elevation	Texture Slope Product	Basin Perimeter
Schumm, 1969	*	*	*	*	*	*									X	
Stall & Fok, 1967											X					
Thomas & Benson, 1970	X						*		X	*						
Walsh, 1972											X					
Frequency	15	6	6	5	4	4	4	3	3	3	3	2	2	2	1	1

X = Primary variable
* = Variable measured in order to derive primary variable

various indices of basin shape as estimates of runoff-rainfall ratios. Basin elongation and circularity exhibited significant correlations with the runoff-rainfall ratios for 25 watersheds on the Appalachian Plateau. Mean annual discharge for the same basins was correlated with area, total stream length, relief ratio, basin shape, mainstream slope, and stream frequency (Morisawa, 1962). She also found a direct correlation between mainstream length and mean annual discharge for 96 watersheds in six different physiographic regions of the eastern U.S. Mustonen (1967) examined climatic and watershed variables affecting annual runoff in Finland, including drainage area. Rakhmanov and Babak (1971) used climatic and watershed variables in a multiple regression analysis to predict mean annual runoff in tributaries of the Upper Volga River. Morphometric variables included area, mainstream slope, and mean elevation. Schumm (1969) related texture-slope product to mean annual runoff for seven basins in New Mexico. Stall and Fok (1967) correlated stream order with various indices of flow duration (10, 50, 90%) for eight stations in the Embarras River basin in Illinois.

Predictors of Base Flow

A review of the literature revealed eight morphometric variables which have been used to estimate or predict base flow, or some other index of low flows (Table VI). Carlston (1963) found an inverse relationship between the square of drainage density and base flow for thirteen eastern U.S. basins. Giusti (1962) correlated basin area with the seven-day drought flow. Orsborn (1970) presented a graphical correlation between the square of drainage density and base flow indicating an inverse relationship for five drift-covered basins in north-central Wisconsin. The work of Stall and Fok (1967) is mentioned again relating stream order to various indices of flow duration, including low flows. Thomas and Benson (1970) employed multiple regression analysis to estimate the annual minimum seven-day mean flow. Area, mainstream slope, and mean elevation were used in the regression. Trainer (1969) found that base flow is inversely proportional to drainage density for ten basins in the Piedmont and Blue Ridge Provinces. Wright (1970)

TABLE VI. MORPHOMETRIC VARIABLES USED TO ESTIMATE BASE FLOWS.

REFERENCE	Area	Drainage Density	Total Stream Length	Mainstream Slope	Mainstream Relief	Mainstream Length	Mean Elevation	Stream Order
Carlston, 1963	*	X	*					
Giusti, 1962	X							
Orsborn, 1970		X						
Stall & Fok, 1967								X
Thomas & Benson, 1970	X			X	*	*	X	
Trainer, 1969	*	X	*					
Wright, 1970	X							
Frequency	5	3	2	1	1	1	1	1

X = Primary variable
* = Variable measured in order to derive primary variable

related area, lithology, slope, and annual runoff to the lowest annual flows in the Lothians River in Scotland using a multiple correlation approach.

Predictors of Peak Flows

A review of the literature revealed twenty-one morphometric variables which have been used to estimate or predict peak flows (Table VII). Anderson and Trobitz (1949) used multiple regression analysis to relate peak discharge from a 1938 flood in forty southern California watersheds to area and other watershed characteristics. Benson (1959, 1962) found that mainstream slope and drainage area were the most important morphometric variables for estimating annual peak floods for 170 gaging stations in New England. Benson (1964) also found that area, mainstream slope, basin length, basin relief, basin slope, and mean elevation relate to peak discharge of several recurrence intervals in a multiple regression for basins in the western Gulf of Mexico region of the U.S. Bigwood and Thomas (1955) found that the mean annual flood for ungaged basins in Connecticut can be estimated by a formula which includes area and mainstream slope. Black (1972) used laboratory watersheds to study the effect of watershed characteristics on hydrograph parameters. Area, drainage density, and basin shape were found to be the most effective morphometric indices of maximum peak flows. Brush (1961) related mean annual flood to area for sixteen streams in central Pennsylvania. Carlston (1963) found that the mean annual flood varies with the square of drainage density for fifteen gaging stations in the eastern U.S. Getty and McHughs (1962) used area, mainstream slope, and length to basin center to estimate peak discharge for ungaged basins in the foothill region of Arkansas and Missouri. Giusti (1962) related area to the median annual flood for twenty-two basins in the Piedmont Province in Virginia. Gupta et al. (1969) correlated peak flows calculated by the unit hydrograph method to area, mainstream length, mainstream slope, and length to basin center. Hickok et al. (1969) used area, mainstream slope, drainage density, and basin width to predict peak flows with an assumed total volume of runoff. Howe et al. (1966) found a direct relationship between drainage density and mean annual flood per unit

TABLE VII. MORPHOMETRIC VARIABLES USED TO ESTIMATE PEAK FLOWS.

REFERENCE	Area	Mainstream Length	Mainstream Slope	Mainstream Relief	Total Stream Length	Drainage Density	Basin Length	Length to Center of Basin	Stream Order	Basin Relief	Basin Width	Basin Shape	Stream Frequency	Total Stream Numbers	Relief Ratio	Bifurcation Ratio	Mean Elevation	Stream Length Ratio	Stream Slope Ratio	Ruggedness Number
Anderson & Trobitz, 1949	X															*		*	*	
Benson, 1959	X	*	X	*																
Benson, 1962	X	*	X	*																
Benson, 1964	X	*	X	*			X			X		X					X			
Bigwood & Thomas, 1955	X	*	X	*																
Black, 1972	X				*	X						X								
Brush, 1961	X																			
Carlston, 1963	*				*	X														
Getty & McHughs, 1962	X	X	X	*				X												
Giusti, 1962	X																			
Gupta et al, 1969	X	X	X	*				X												
Hickok et al, 1959	X	*	X	*	*	X					X									
Howe et al, 1966	*				*	X														
Jarvis, 1936	X						X				X									
Leopold & Miller, 1956	X								X											
Morisawa, 1962	X				X		*			*		X	X	*	X					
Orsborn, 1970						X														
Patton & Baker, 1976	*				*	X	*		X	*			X	*	X					X

TABLE VII. Continued

REFERENCE	Area	Mainstream Length	Mainstream Slope	Mainstream Relief	Total Stream Length	Drainage Density	Basin Length	Length to Center of Basin	Stream Order	Basin Relief	Basin Width	Basin Shape	Stream Frequency	Total Stream Numbers	Relief Ratio	Bifurcation Ratio	Mean Elevation	Stream Length Ratio	Stream Slope Ratio	Ruggedness Number
Potter, 1953	X	X	X	*																
Stall & Fok, 1967									X											
Taylor & Schwartz, 1952	X	X	X	*				X												
Thomas & Benson, 1970	X	X	X	*							X					X	X			
Wong, 1963		X																		
Wong, 1971		X																		
Frequency	20	12	10	10	6	6	4	3	3	3	3	3	2	2	2	2	2	1	1	1

X = Primary variable
* = Variable measured in order to derive primary variable

area for twelve basins in Wales. Jarvis (1936) provided an early summary of formulas for estimating floods involving area, basin length, and basin width. Leopold and Miller (1956) estimated mean annual peak flow for ephemeral streams in New Mexico using area and stream order. Morisawa (1962) found that peak flows in twenty-five Appalachian watersheds are correlated with area, total stream length, basin shape, stream frequency, and relief ratio. Orsborn (1970) correlated mean annual flood for five drift-covered basins in north-central Wisconsin with the square of drainage density. Patton and Baker (1976) used drainage density, stream order, stream frequency, relief ratio, and ruggedness number to measure flood potential for basins in central Texas, the Wasatch Front, southern California, Indiana, and the Appalachian Plateau. Potter (1953) related area, mainstream length, and mainstream slope with peak flow for a ten-year interval storm in a multiple correlation analysis of fifty-one watersheds in the Allegheny-Cumberland Plateau. Stall and Fok (1967) correlated stream order with various indices of flow duration, including high flows. Taylor and Schwartz (1952) correlated area, mainstream length, mainstream slope, and length to basin center with peak flow values for twenty basins in the north and mid-Atlantic states. Thomas and Benson (1970) used several morphometric variables in a multiple regression analysis to estimate flood peaks with return intervals of 1.2, 2, 5, 10, 20, 25, and 50 years. The most useful estimates were area, mainstream length, mainstream slope, basin width, bifurcation ratio, and mean elevation. Wong (1963, 1971) used mainstream length and other variables to estimate mean annual flood and peak flows of other recurrence intervals for 90 gaged basins in New England.

Predictors of Sediment Yield

A review of the literature revealed twenty morphometric variables which have been used to estimate or predict sediment yield (Table VIII). Anderson (1961) developed a regression model for predicting suspended sediment discharge, based on ten independent variables, including area and mainstream slope. Anderson and Trobitz (1949) found that storm period reservoir sedimentation was related to area and bifurcation

TABLE VIII. MORPHOMETRIC VARIABLES USED TO ESTIMATE SEDIMENT YIELD.

REFERENCE	Area	Relief Ratio	Basin Relief	Basin Length	Total Stream Length	Drainage Density	Bifurcation Ratio	Mainstream Slope	Mainstream Relief	Mainstream Length	Elevation	Texture Slope Product	Total # Streams	Transport Efficiency Factor - 1	Transport Efficiency Factor - 2	Basin Shape	Stream Frequency	Stream Slope Ratio	Stream Length Ratio
Anderson, 1961	X							X	*	*									
Anderson & Trobitz, 1949	X						X											*	*
Hadley & Schumm, 1961	*	X	*	*	*	X													
Hansen & Painter, 1974	X	X	*	*							X								
Lustig, 1965	X				X		*						*	X	X		X		
Maner, 1958	X	X	X	X	*	X										X			
Schumm, 1954		X	*	*															
Schumm, 1956		X	*	*															
Schumm, 1969	*	*	*	*	*	*						X							
Frequency	7	6	6	6	4	3	2	1	1	1	1	1	1	1	1	1	1	1	1

X = Primary variable
* = Variable measured in order to derive primary variable

ratio, among other watershed and climatic variables. Hadley and Schumm (1961) related relief ratio and drainage density to rates of sediment accumulation in eleven reservoirs in Utah, New Mexico, and Arizona and a separate graphical correlation for twenty-six basins in the Cheyenne River basin. Hansen and Painter (1974) found a significant multiple correlation between average annual sediment yield and area, relief ratio, and elevation for seventy-nine large basins distributed worldwide. Lustig (1965) predicted sediment yield using area, total stream length, stream frequency and two transport efficiency factors using data from instrumented watersheds in the San Gabriel Mountains of southern California. Maner (1958) correlated sediment delivery rate with area, relief ratio, basin relief, basin length, drainage density, and basin shape for twenty-five watersheds in the Red Hills physiographic region of southern Kansas, western Oklahoma, and western Texas. Studies by Schumm (1954, 1956, 1969) established correlations with relief ratio, texture-slope product and sediment yield for semi-arid basins.

RESULTS OF CORRELATION ANALYSIS

All streamflow and sediment data for the study basins are normalized on an area-yield basis. Mean annual runoff is expressed in inches. Base flow is expressed in cubic feet per second per square mile (csm) and is calculated for each year as the mean of minimum average daily flows for each month, after the method used by Carlston (1963). Mean annual peak flow is calculated using annual series data with the log-Pearson type III distribution, and is also expressed in csm. Mean annual sediment yield is expressed in tons per square mile.

Mean annual runoff, base flow, mean annual peak flow, and mean annual sediment yield are calculated for each of the control watersheds using data for the entire period of record. Annual values for each year in the calibration period are used to derive a correlation between the control watershed and paired watersheds. The mean value for the control watershed is entered into the regression equation to determine the corresponding value for the treatment watersheds. This procedure has

the advantage of accounting for climatic variation affecting streamflow and sediment yield after the watersheds have been logged, without reflecting the influence of timber harvest (Tables IX-XII). Only correlations significant at the .10 level are used, thereby excluding the value for sediment yield for HJA-6.

Mean annual runoff, base flow, mean annual peak flow, and mean annual sediment yield are correlated against each of the morphometric variables which is not related to area and which has been used with some success for estimating or predictive purposes. These criteria restrict the correlation studies to the following basin and stream network variables:

mainstream slope	circularity
drainage density	basin elongation
relief ratio	form factor-1
texture-slope product	form factor-2
stream frequency	compactness coefficient
	lemniscate

Because of the lithologic and climatic controls on basin and stream network morphometry, some groups of watersheds are treated as outliers in a specific correlation. For example, the Alsea Experimental Watersheds are treated as outliers in the correlation of mainstream slope and mean annual runoff (Figure 9). The resultant correlation is thus considered valid only for igneous lithologies and does not apply to basins underlain by sedimentary parent materials. One must establish not only whether a statistically significant correlation exists between the variables analyzed, but also whether there is a physical (hydrologic and geomorphic) basis for the relationship. Scatter diagrams are presented for all correlations which can be measured in this manner and which are statistically significant at the .10 level (Figures 9-27). The correlation is termed highly significant if the t^* value indicates a significant correlation at the .05 level. A regression line is shown for prediction purposes treating the morphometric variable as the "independent" variable and the streamflow or sediment value as the "dependent" variable.

TABLE IX. CORRELATION OF MEAN ANNUAL RUNOFF BETWEEN CONTROL AND TREATMENT WATERSHEDS FOR CALIBRATION PERIOD.

BASIN	CALIBRATION PERIOD	YEARS	REGRESSION EDUCATION	r^2	t^*	PROBABILITY OF CHANCE CORRELATION	MEAN ANNUAL RUNOFF (in.)
HJA-1 (Y)	1953-1962	10	Y = .559 + .864(X)	.722	4.56	.01	48.7
HJA-2 (Control, X)	1953-1977	25	--	--	--	--	55.7
HJA-3 (Y)	1953-1958	6	Y = -1.90 + .906(X)	.967	10.8	.001	48.6
HJA-6 (Y)	1964-1974	11	Y = -.783 + 1.15(X)	.882	8.20	.001	55.2
HJA-7 (Y)	1964-1974	11	Y = -1.98 + .830(X)	.984	23.5	.001	38.4
HJA-8 (Control, X)	1964-1977	14	--	--	--	--	48.7
HJA-9 (Control, X)	1969-1977	9	--	--	--	--	51.9
HJA-10 (Y)	1969-1975	7	Y = 5.79 + 1.06(X)	.989	21.2	.001	38.4
Flynn Creek (Control, X)	1959-1973	15	--	--	--	--	76.7
Deer Creek (Y)	1959-1965	7	Y = -5.00 + 1.03(X)	.975	14.0	.001	74.0
Needle Branch (Y)	1959-1965	7	Y = 3.56 + .908(X)	.793	4.38	.01	73.4
CC-1 (Y)	1966-1971	6	Y = .518 + .906(X)	.994	25.7	.001	21.3
CC-2 (Y)	1966-1971	6	Y = -.685 + .852(X)	.995	28.2	.001	18.8
CC-3 (Y)	1966-1971	6	Y = =.201 + .917(X)	.998	44.7	.001	20.8
CC-4 (Control, X)	1966-1977	12	--	--	--	--	22.9

Source: data for control watersheds supplied by R.D. Harr and R.L. Fredrikson, Forest Science Laboratory, Corvallis, Oregon.

TABLE X. CORRELATION OF BASE FLOWS BETWEEN CONTROL AND TREATMENT WATERSHEDS FOR CALIBRATION PERIOD.

BASIN	CALIBRATION PERIOD	YEARS	REGRESSION EDUCATION	r^2	t^*	PROBABILITY OF CHANCE CORRELATION	BASE FLOW (csm)
HJA-1 (Y)	1953-1962	10	Y = -.0144 + .695(X)	.867	7.22	.001	.945
HJA-2 (Control, X)	1953-1977	25	--	--	--	--	1.38
HJA-3 (Y)	1953-1958	6	Y = -.155 + .995(X)	.663	2.63	.01	1.22
HJA-6 (Y)	1964-1974	11	Y = -.0479 + 1.35(X)	.986	25.2	.001	1.53
HJA-7 (Y)	1964-1974	11	Y = .00583 + .898(X)	.955	13.8	.001	1.06
HJA-8 (Control, X)	1964-1977	14	--	--	--	--	1.17
HJA-9 (Control, X)	1969-1977	9	--	--	--	--	1.03
HJA-10 (Y)	1969-1975	7	Y = .357 + .647(X)	.866	5.68	.01	1.02
Flynn Creek (Control, X)	1959-1973	15	--	--	--	--	1.95
Deer Creek (Y)	1959-1965	7	Y = -.312 + 1.06(X)	.920	7.58	.001	1.76
Needle Branch (Y)	1959-1965	7	Y = -.671 + 1.08(X)	.830	4.94	.01	1.44
CC-1 (Y)	1966-1971	6	Y = 1.14(X)	.991	21.0	.001	.474
CC-2 (Y)	1966-1971	6	Y = -.0274 + .894(X)	.968	11.0	.001	.340
CC-3 (Y)	1966-1971	6	Y = .0173 + .957(X)	.987	17.4	.001	.419
CC-4 (Control, X)	1966-1977	12	--	--	--	--	.416

TABLE XI. CORRELATION OF MEAN ANNUAL PEAK FLOWS (LOG PEARSON TYPE III ANALYSIS, ANNUAL DATA SERIES) BETWEEN CONTROL AND TREATMENT WATERSHEDS FOR CALIBRATION PERIOD.

BASIN	CALIBRATION PERIOD	YEARS	REGRESSION EDUCATION	r^2	t^*	PROBABILITY OF CHANCE CORRELATION	MEAN ANNUAL PEAK FLOW (csm)
HJA-1 (Y)	1953-1962	10	Y = 20.0 + .808(X)	.884	7.81	.001	77
HJA-2 (Control, X)	1953-1977	25	--	--	--	--	70
HJA-3 (Y)	1953-1958	6	Y = -11.4 + 1.06(X)	.961	9.93	.001	63
HJA-6 (Y)	1964-1974	11	Y = 1.90 + 1.14(X)	.939	11.8	.001	73
HJA-7 (Y)	1964-1974	11	Y = -6.54 + .975(X)	.981	21.6	.001	54
HJA-8 (Control, X)	1964-1977	14	--	--	--	--	62
HJA-9 (Control, X)	1969-1977	9	--	--	--	--	71
HJA-10 (Y)	1969-1975	7	Y = 1.28 + 1.24(X)	.871	5.81	.01	89
Flynn Creek (Control, X)	1959-1973	15	--	--	--	--	74
Deer Creek (Y)	1959-1965	7	not given	--	--	--	78
Needle Branch (Y)	1959-1965	7	not given	--	--	--	99
CC-1 (Y)	1966-1971	6	not given	--	a	a	31
CC-2 (Y)	1966-1971	6	not given	--	a	a	38
CC-3 (Y)	1966-1971	6	not given	--	a	a	37
CC-4 (Control, X)	1966-1972	12	--	--	a	a	46

a = not available

Source: data for control watersheds supplied by R.D. Harr and R.L. Fredrikson, Forest Science Laboratory, Corvallis, Oregon.

TABLE XII. CORRELATION OF ANNUAL SEDIMENT YIELDS BETWEEN CONTROL AND TREATMENT WATERSHEDS FOR CALIBRATION PERIOD.

BASIN	CALIBRATION PERIOD	YEARS	REGRESSION EDUCATION	r^2	t^*	PROBABILITY OF CHANCE CORRELATION	ANNUAL SEDIMENT YIELD (tons/mi.^{2})
HJA-1 (Y)	1957-1962	6	Y = -.260 + .902(X)	.984	15.7	.001	28.7
HJA-2 (Control, X)	1957-1970, 1972-1976	19	--	--	--	--	32.1
HJA-3 (Y)	1957-1958	2	--	--	--	--	--
HJA-6 (Y)	1972-1974	3	Y = 2.99 + .440(X)	.968	5.50	.2	17.3
HJA-7 (Y)	1972-1974	3	Y = 2.43 + .120(X)	.979	6.83	.1	6.34
HJA-8 (Control, X)	1972-1977	6	--	--	--	--	32.6
HJA-9 (Control, X)	1969-1973	5	--	--	--	--	6.50
HJA-10 (Y)	1969-1973	5	Y = .325 + 1.15(X)	.997	31.6	.001	7.80
Flynn Creek (Control, X)	1959-1973	15	--	--	--	--	291
Deer Creek (Y)	1959-1965	7	Y = 35.6 + .817(X)	.996	35.3	.001	274
Needle Branch (Y)	1959-1965	7	Y = 72.7 + .290(X)	.926	7.91	.001	157
CC-1 (Y)	1970-1971	2	--	--	--	--	--
CC-2 (Y)	1970-1971	2	--	--	--	--	--
CC-3 (Y)	1970-1971	2	--	--	--	--	--
CC-4 (Control, X)	1970-1977	8	--	--	--	--	147

Source: data for control watersheds supplied by R.D. Harr and R.L. Fredrikson, Forest Science Laboratory, Corvallis, Oregon.

Highly significant correlations are evident between mean annual runoff and mainstream slope, drainage density, relief ratio, and texture-slope product (Figures 9-12). A significant correlation is exhibited between form factor-2 and mean annual runoff (Figure 13). Drainage density provides the best overall estimate of mean annual runoff, with an r^2 value of .735 and including both igneous and sedimentary lithologies (Figure 10).

Highly significant correlations are found between base flow and relief ratio (Figure 14). Significant correlations are exhibited between base flow and basin elongation and form factors (Figures 15 and 16). However, these latter two correlations only use data from the Alsea Experimental Watersheds and are therefore not useful predictors on basins underlain by igneous parent material. Relief ratio (r^2 = .471) provides the best overall estimate of base flow (Figure 14).

Highly significant correlations are found between mean annual peak flow and mainstream slope, drainage density, texture-slope product, and stream frequency (Figures 17, 18, 20, 21). In addition, a significant correlation is evident between mean annual peak flow and relief ratio (Figure 19). The correlations with drainage density and stream frequency incorporate all study basins, although the latter is deemed most useful because of the higher r^2 value of .487 (Figure 21).

Highly significant correlations are exhibited between mean annual sediment yield and drainage density, circularity, form factor-2, compactness coefficient, and lemniscate (Figures 22-27). However, correlations using the various indices of basin shape (circularity, form factor-1, form factor-2, compactness coefficient, and lemniscate) are derived using only data from the Alsea Experimental Watersheds. Drainage density provides the most useful estimate of sediment yield, with an r_2 value of .425 (Figure 22).

It has now been establilshed that drainage density, relief ratio, stream frequency, and drainage density are the best single estimators of mean annual runoff, base flow, mean annual peak flow, and mean annual sedi-

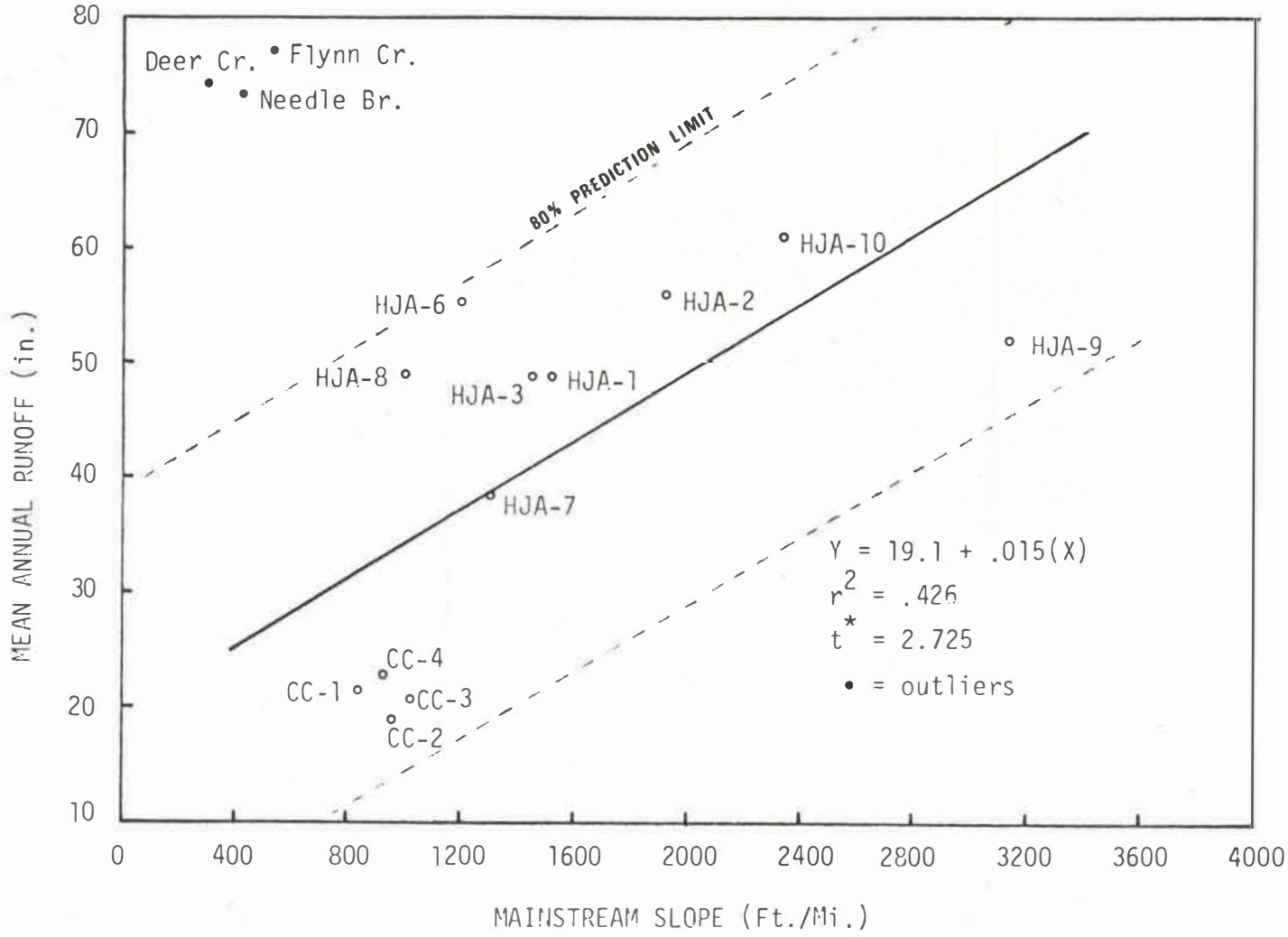

Figure 9. Highly significant correlation between mainstream slope (X) and mean annual runoff (Y). The Alsea Experimental Watersheds are tested as outliers and excluded from the correlation.

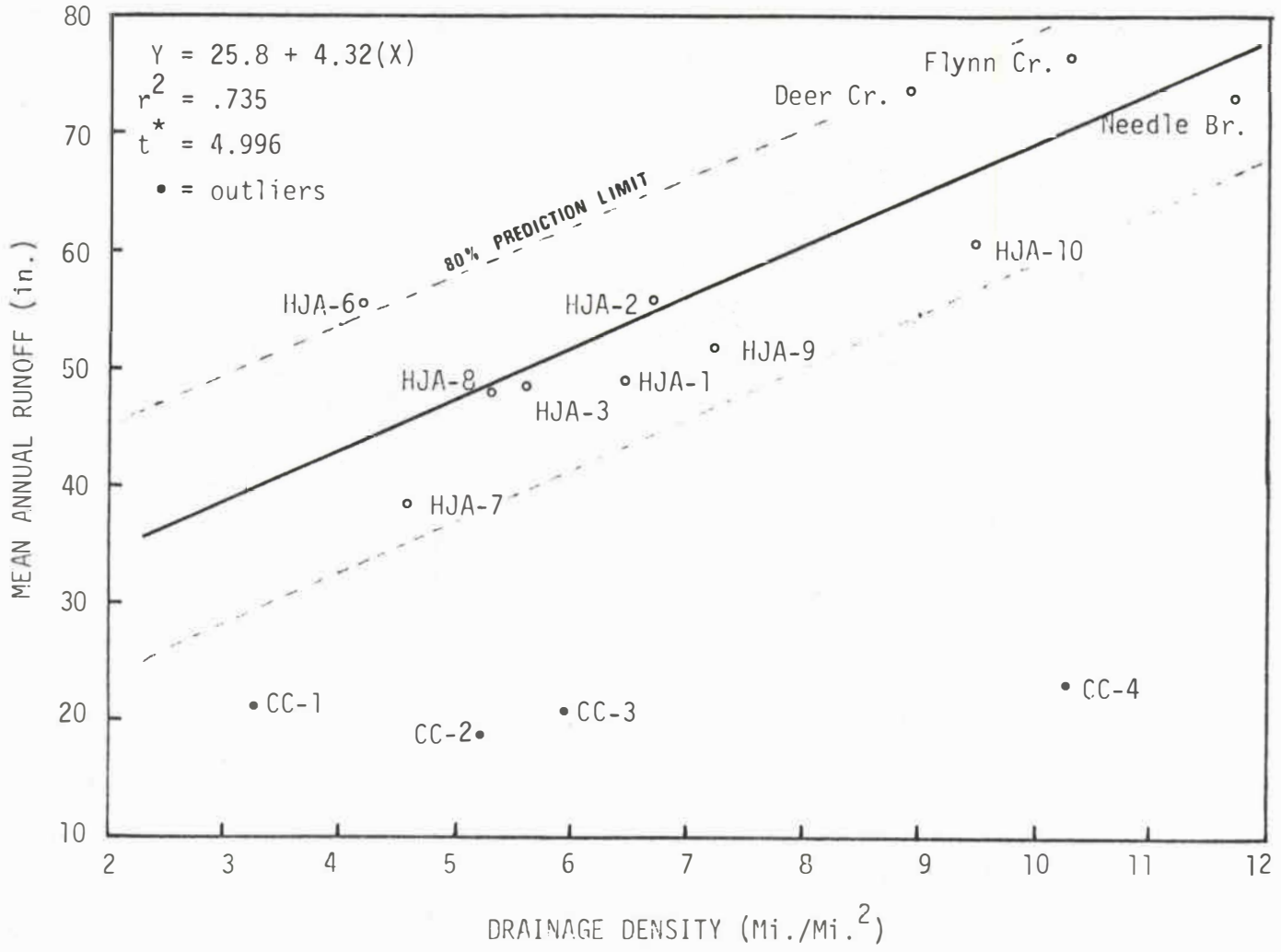

Figure 10. Highly significant correlation between drainage density (X) and mean annual runoff (Y). The Coyote Creek Watersheds are treated as outliers and excluded from the correlation.

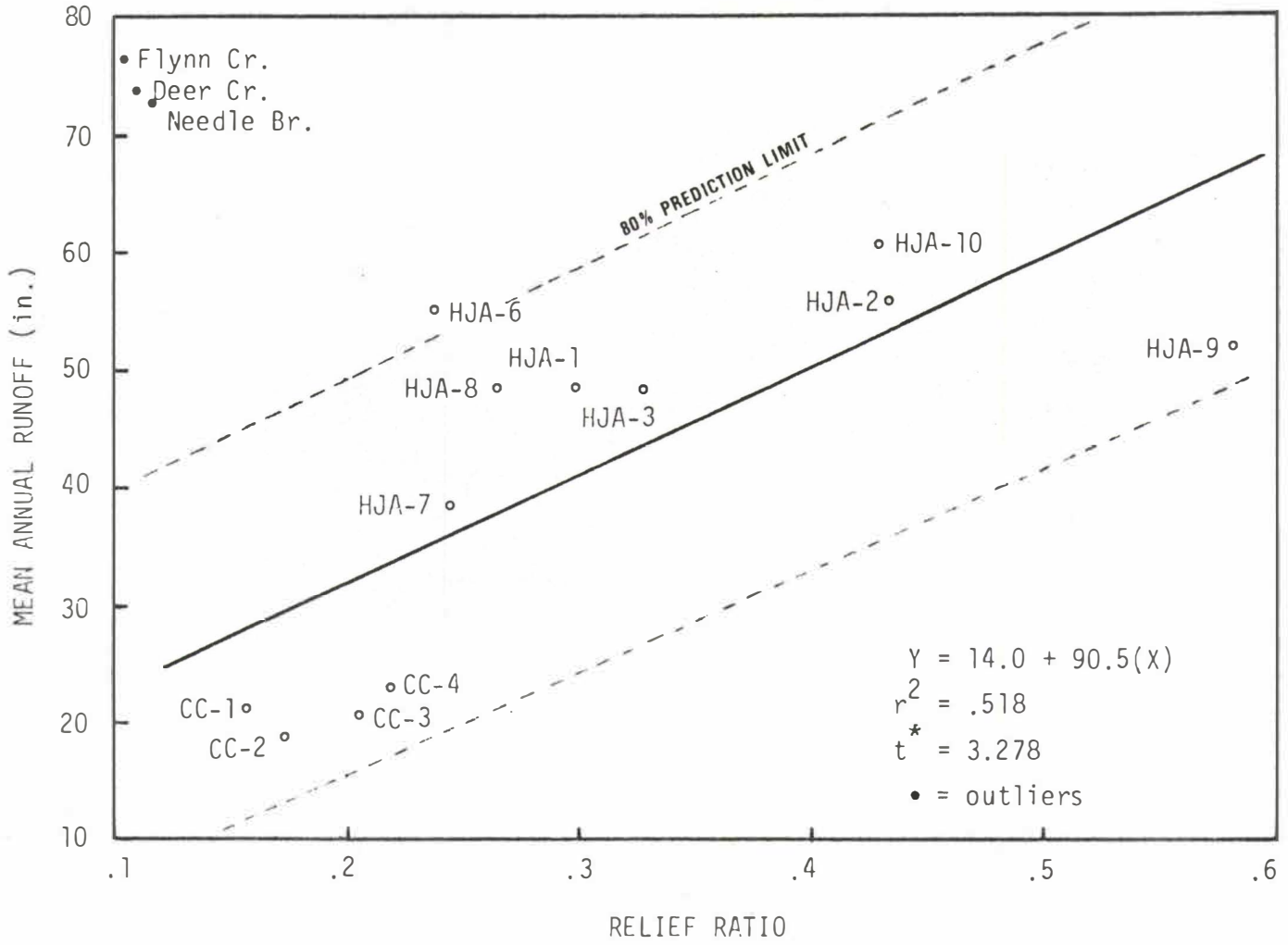

Figure 11. Highly significant correlation between relief ratio (X) and mean annual runoff (Y). The Alsea Experimental Watersheds are treated as outliers and excluded from the correlation.

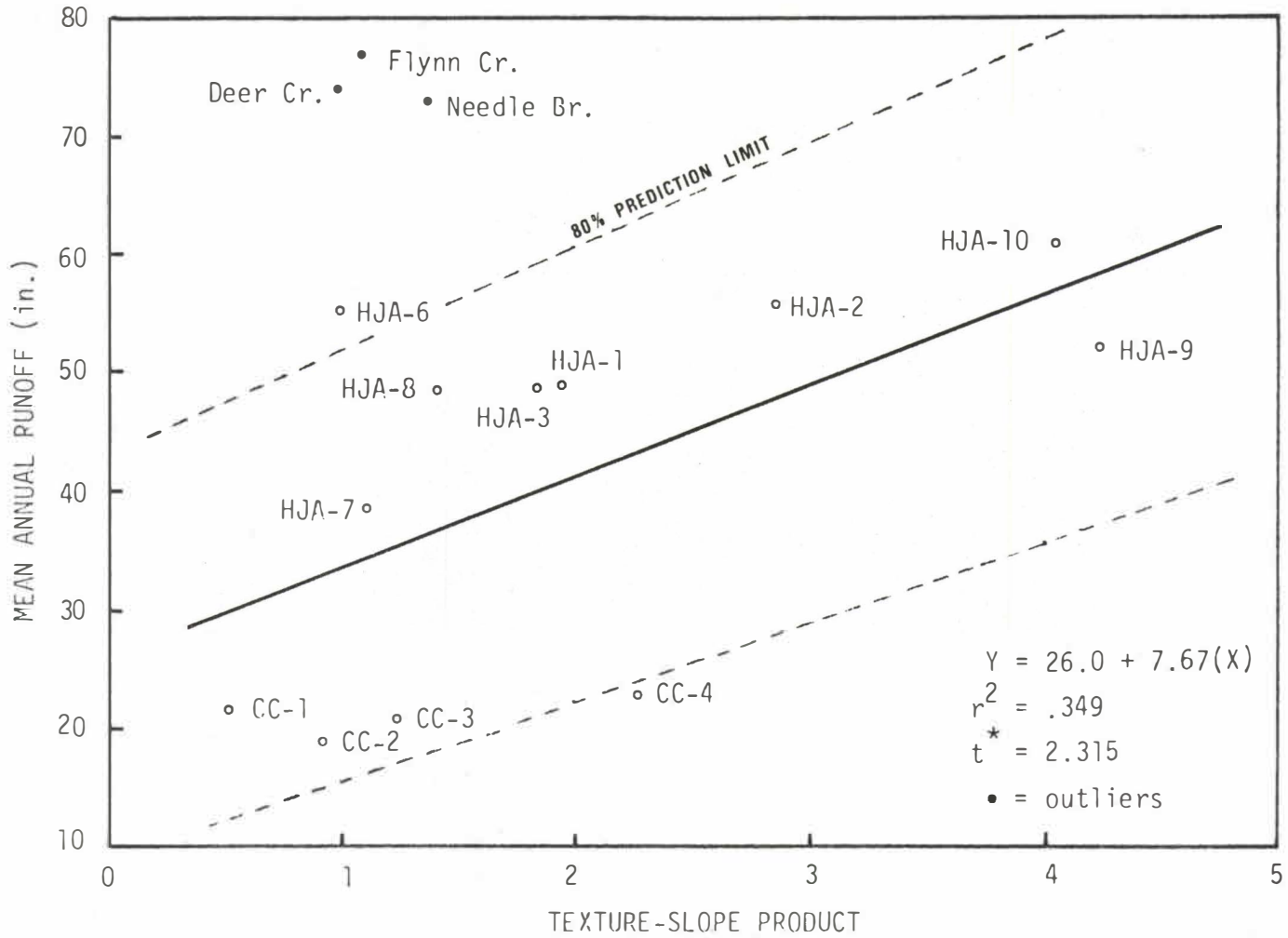

Figure 12. Highly significant correlation between texture-slope product (X) and mean annual runoff (Y). The Alsea Experimental Watersheds and treated as outliers and excluded from the correlation.

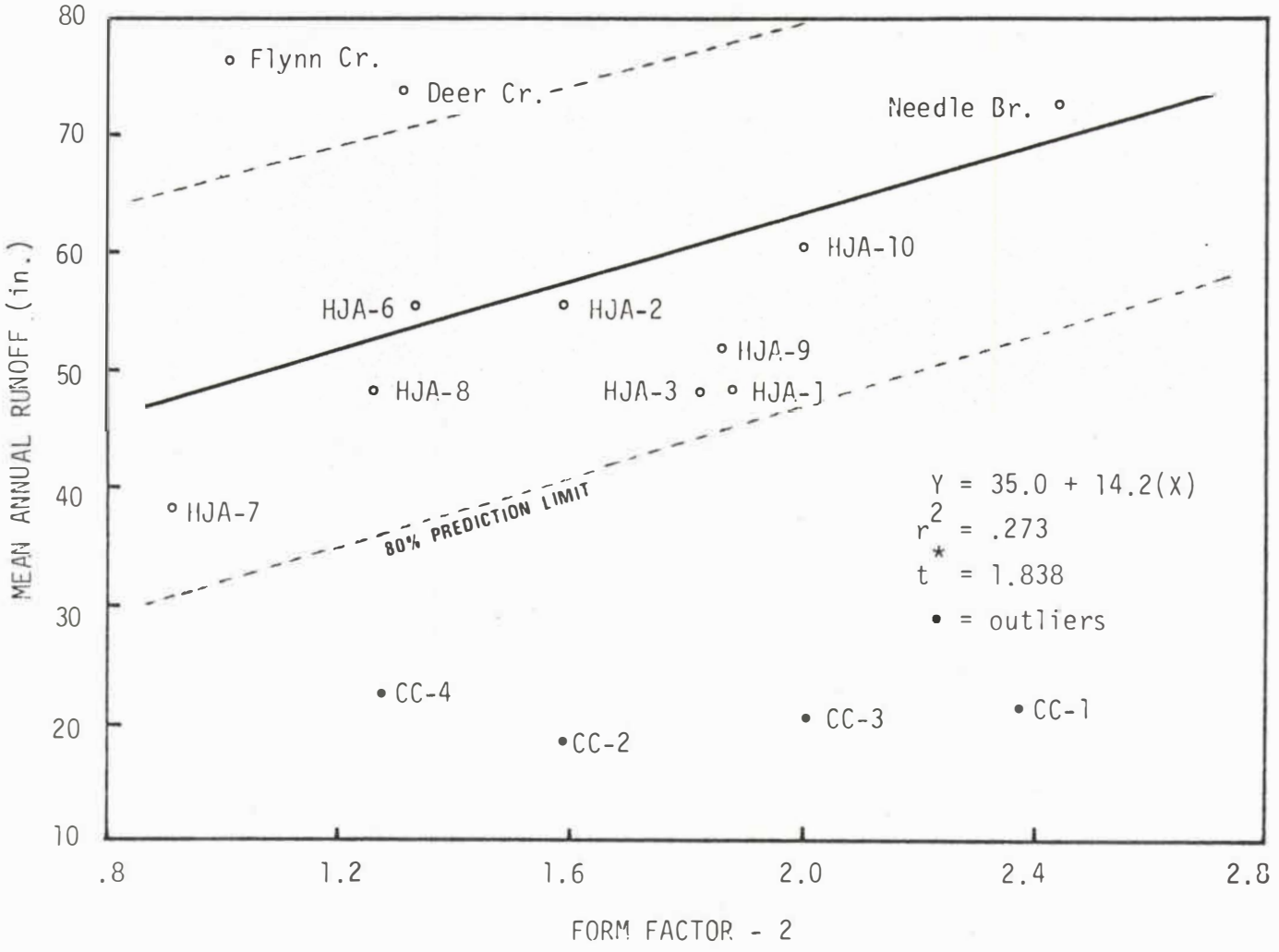

Figure 13. Significant correlation between form factor-2 (X) and mean annual runoff (Y). The Coyote Creek Experimental Watersheds are treated as outliers and excluded from the correlation.

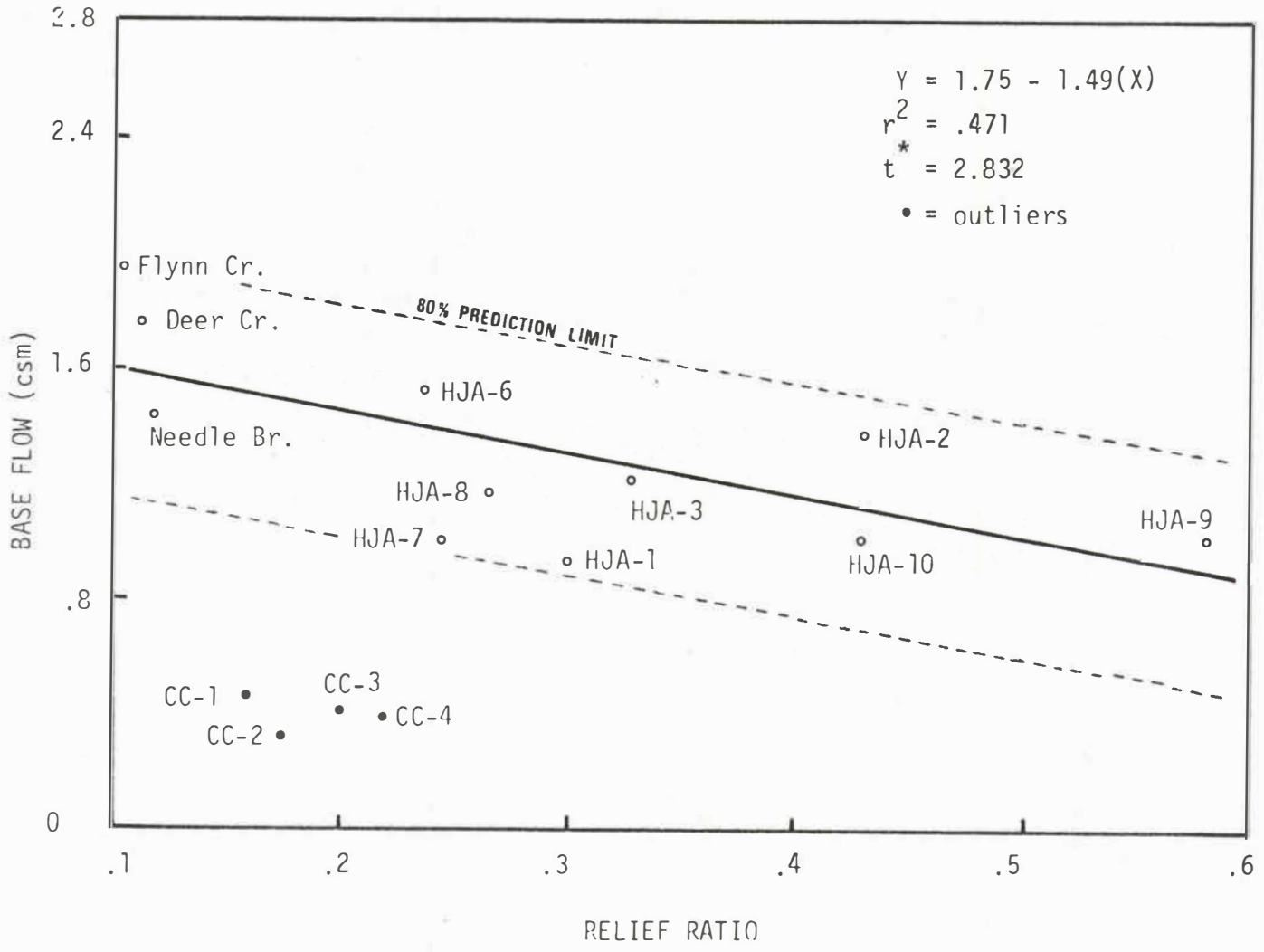

Figure 14. Highly significant correlation between relief ratio (X) and base flow (Y). The Coyote Creek Experimental Watersheds are treated as outliers and excluded from the correlation.

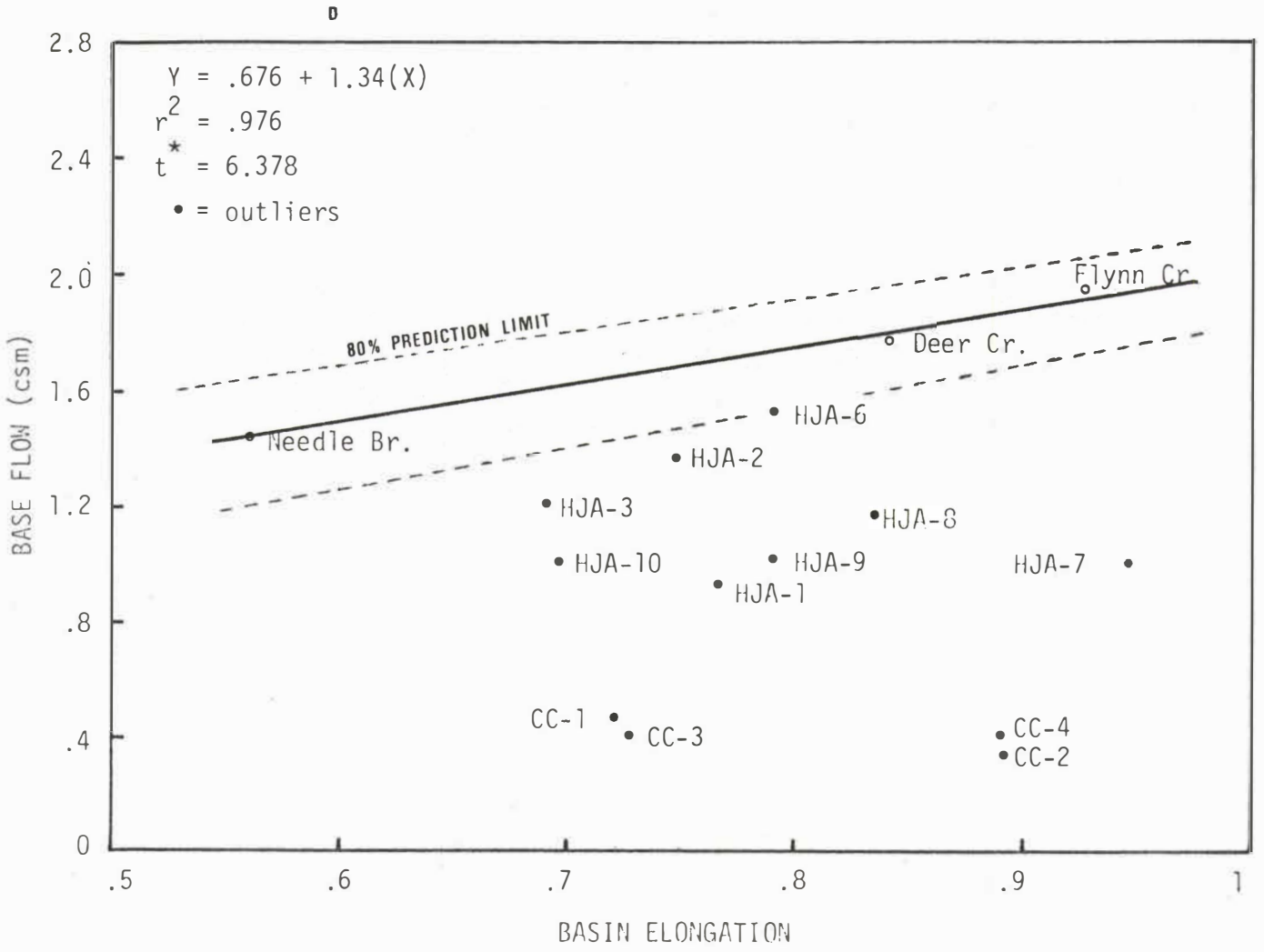

Figure 15. Significant correlation between basin elongation (X) and base flow (Y) for the Alsea Experimental Watersheds. All other study basins are treated as outliers and excluded from the correlation.

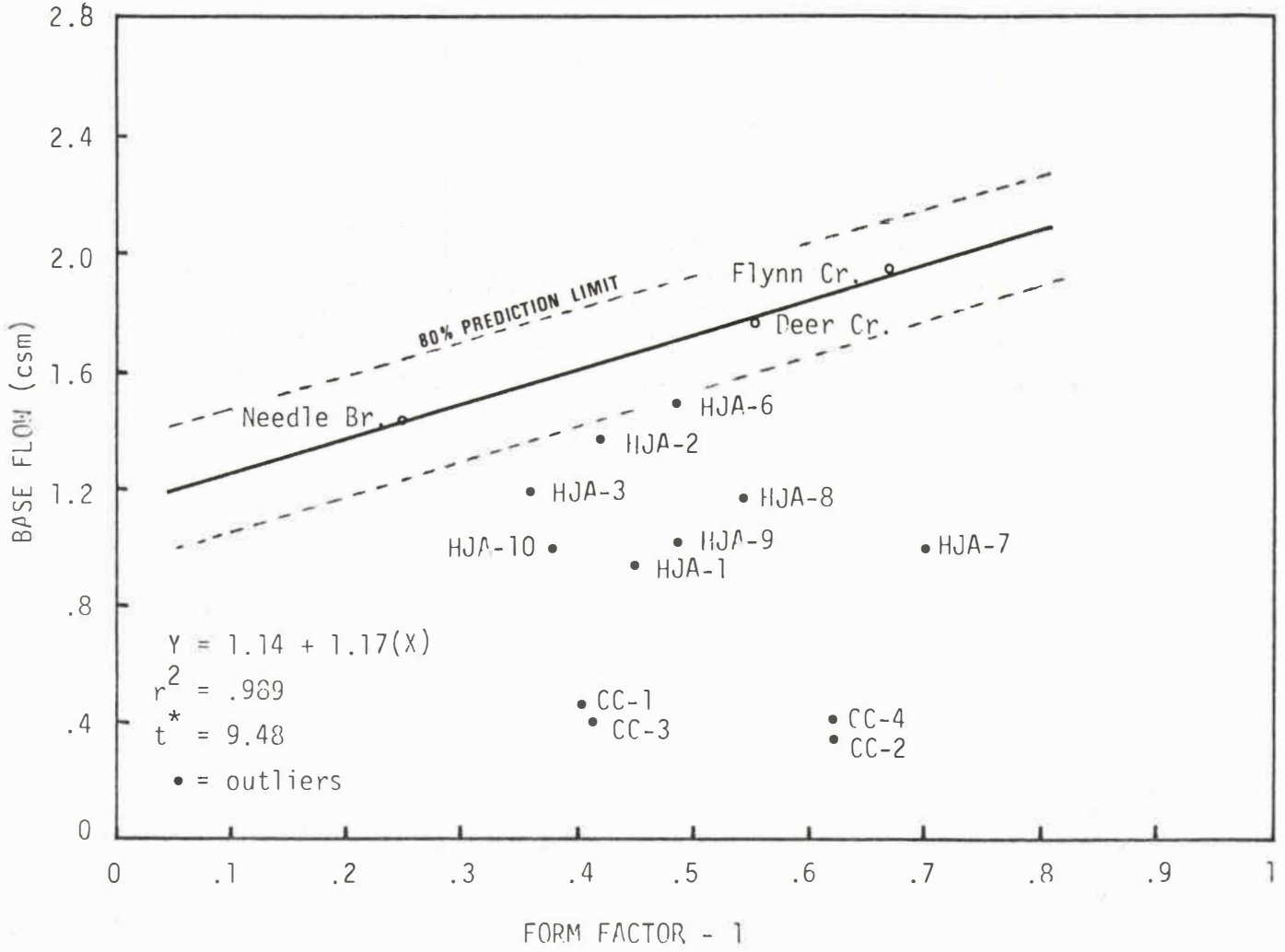

Figure 16. Significant correlation between form factor-1 (X) and base flow (Y) for the Alsea Experimental Watersheds. All other study basins are treated as outliers and excluded from the correlation.

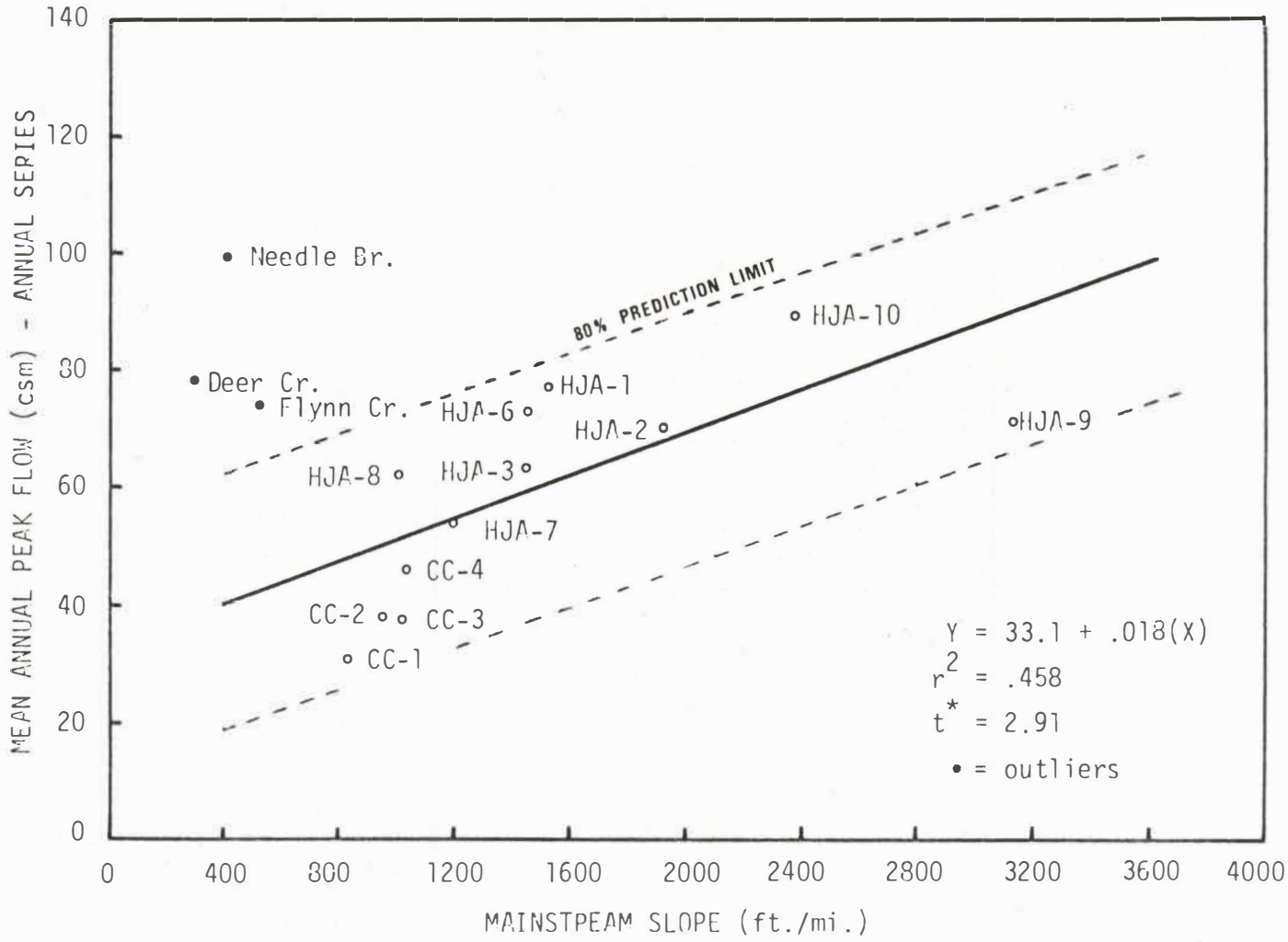

Figure 17. Highly significant correlation between mainstream slope (X) and mean annual peak flow (Y). The Alsea Experimental Watersheds are treated as outliers and excluded from the correlation.

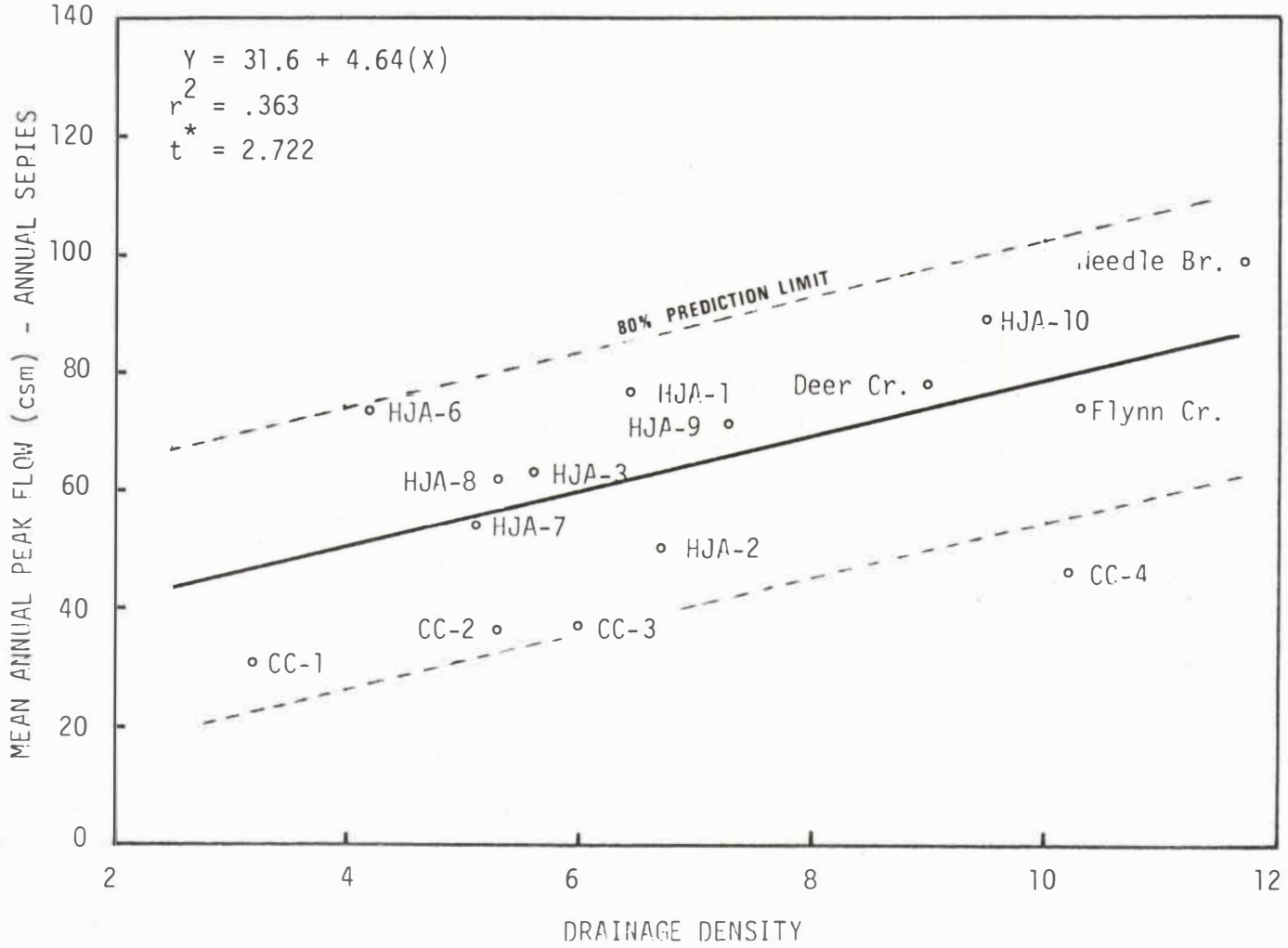

Figure 18. Highly significant correlation between drainage density (X) and mean annual peak flow (Y).

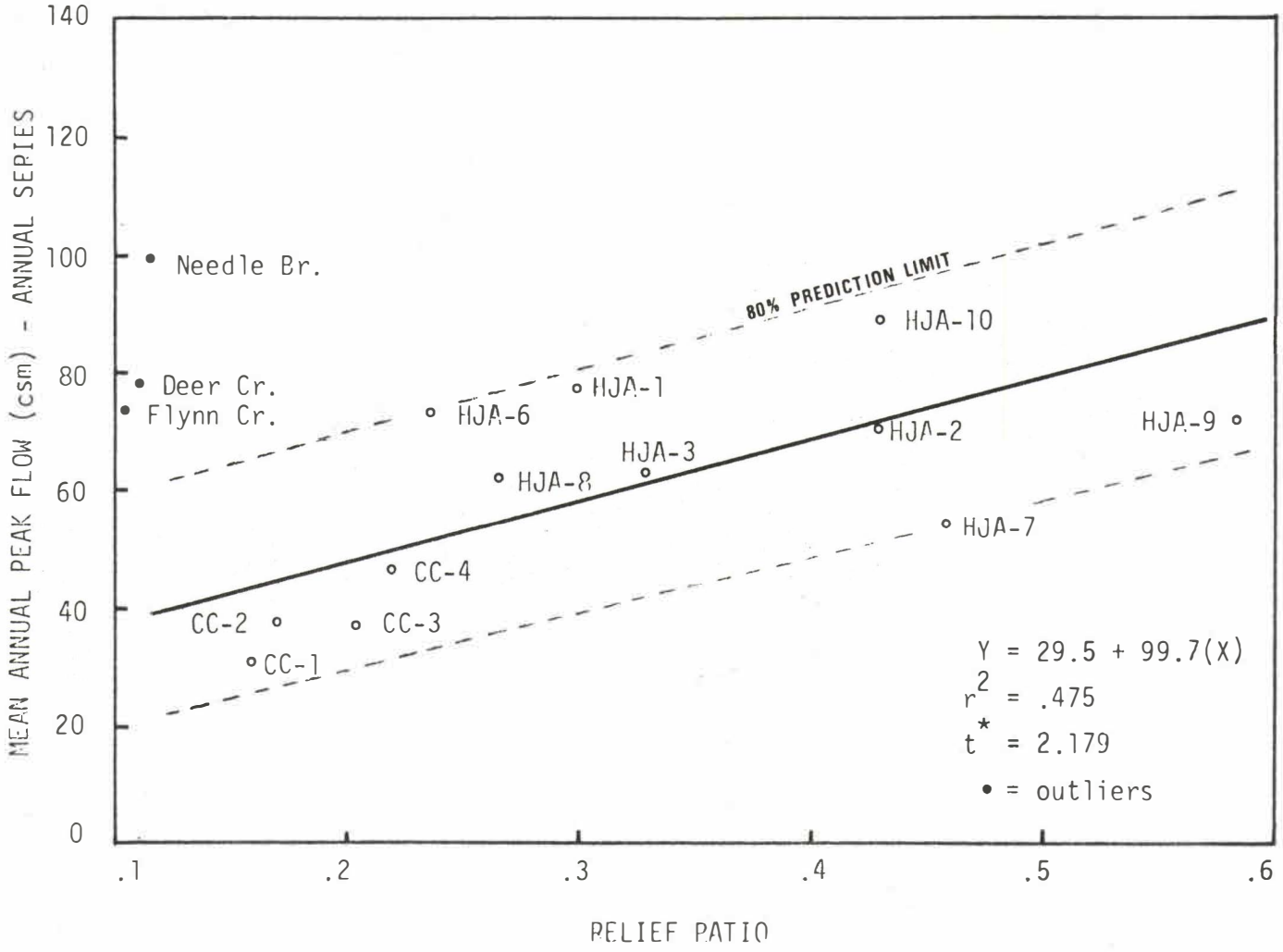

Figure 19. Significant correlation between relief ratio (X) and mean annual peak flow (Y). The Alsea Experimental Watersheds are treated as outliers and excluded from the correlation.

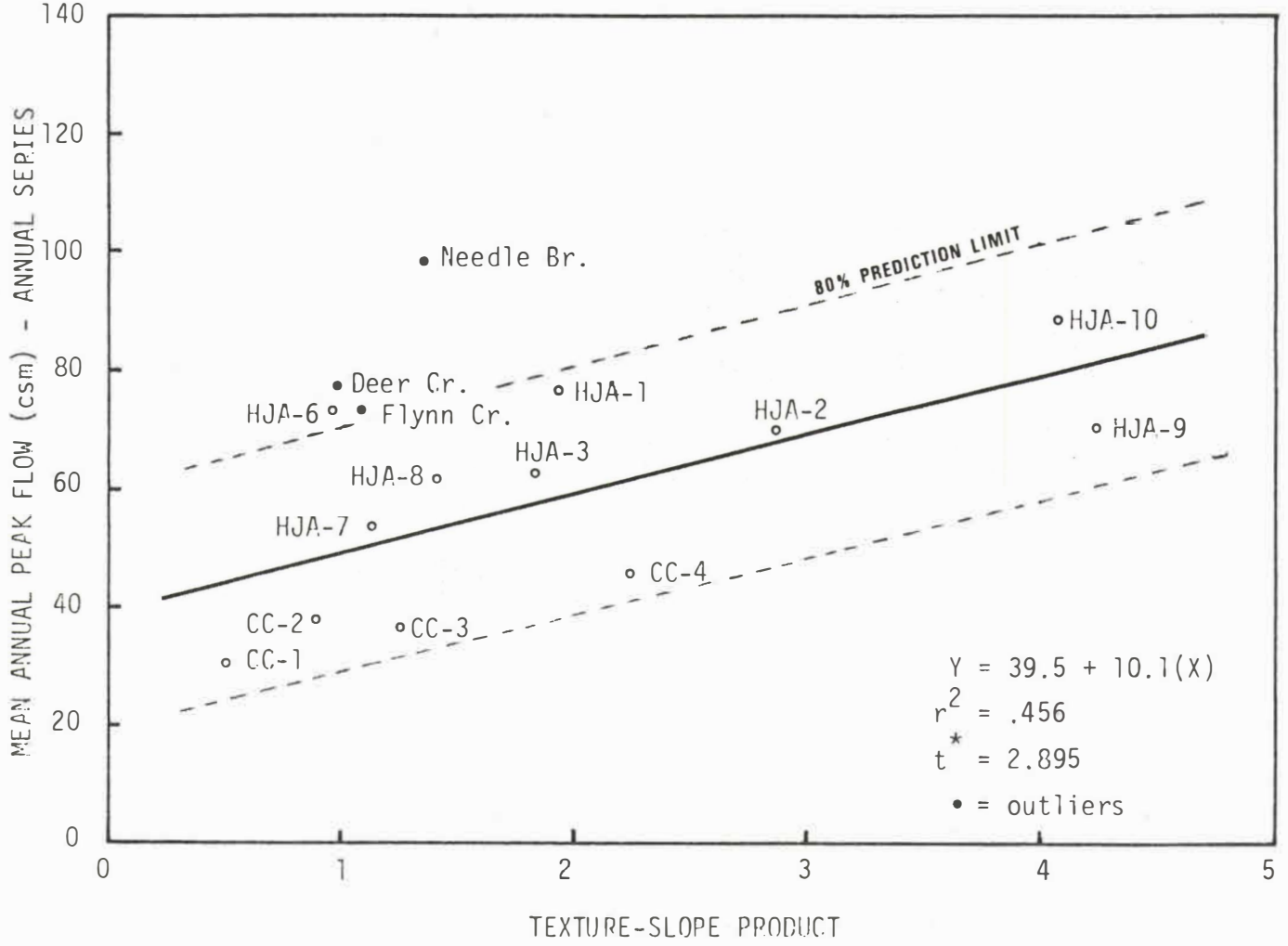

Figure 20. Highly significant correlation between texture-slope product (X) and mean annual peak flow (Y). The Alsea Experimental Watersheds are treated as outliers and excluded from the correlation.

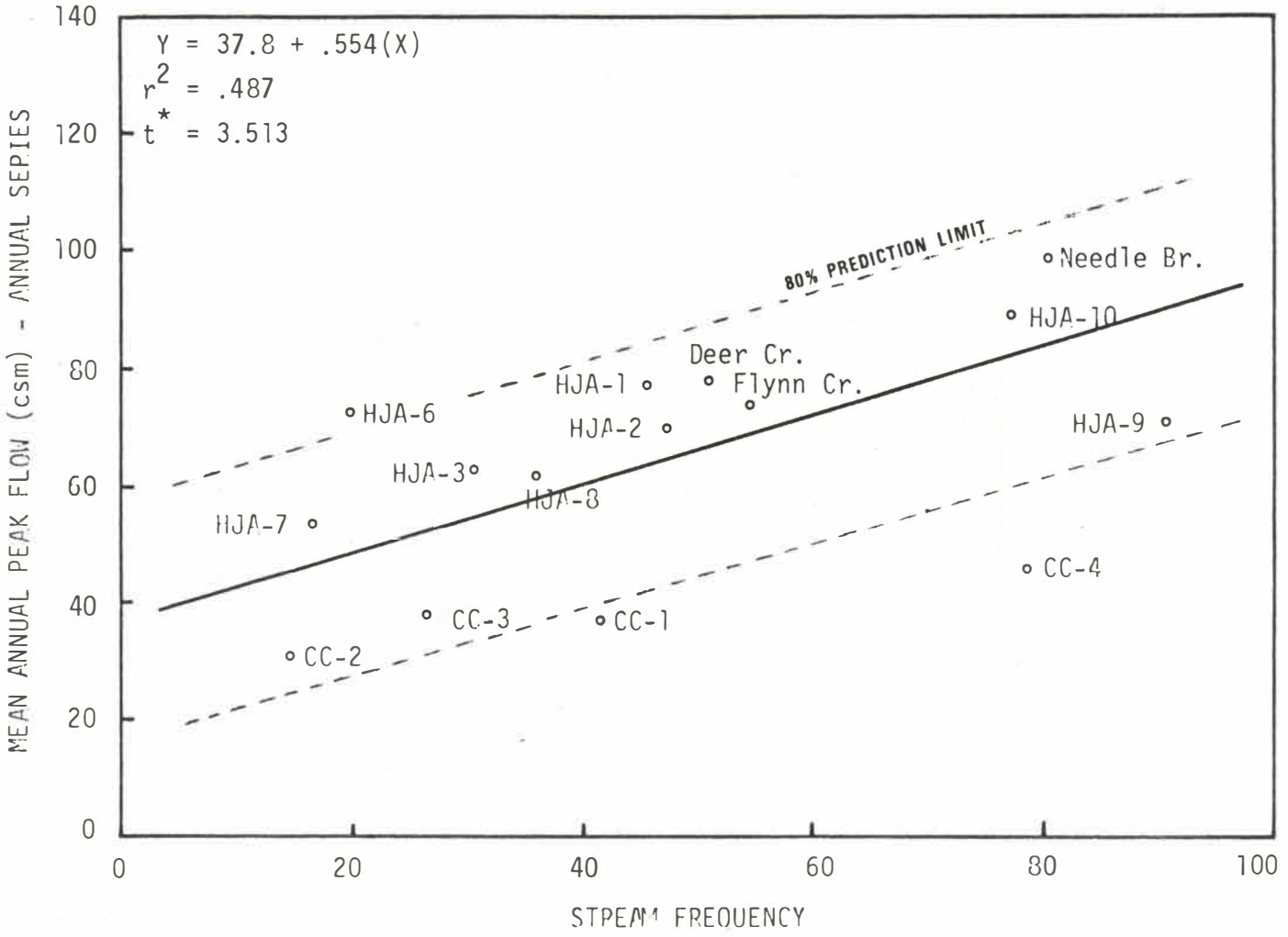

Figure 21. Highly significant correlation between stream frequency (X) and mean annual peak flow (Y).

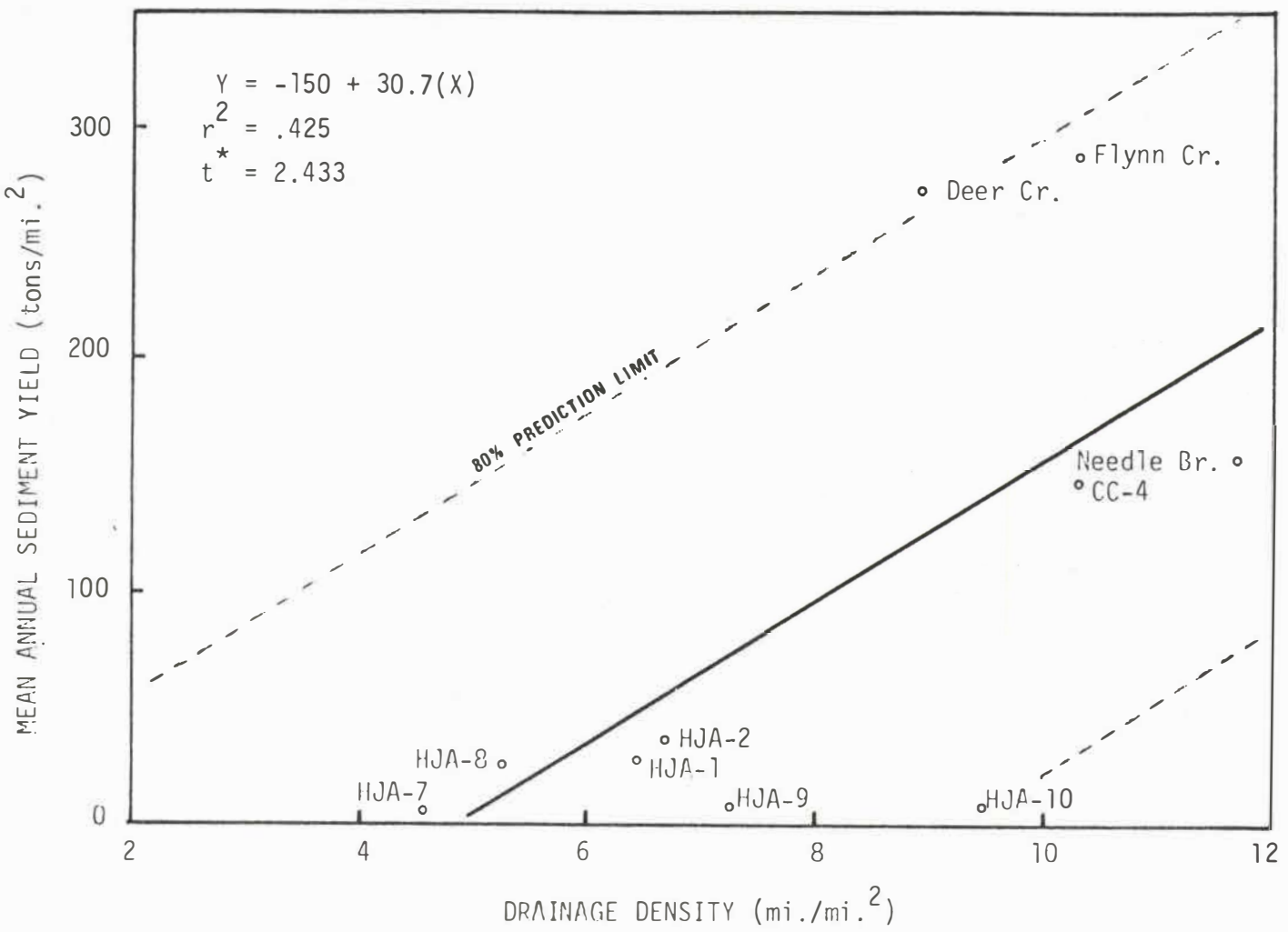

Figure 22. Highly significant correlation between drainage density (X) and mean annual sediment yield (Y).

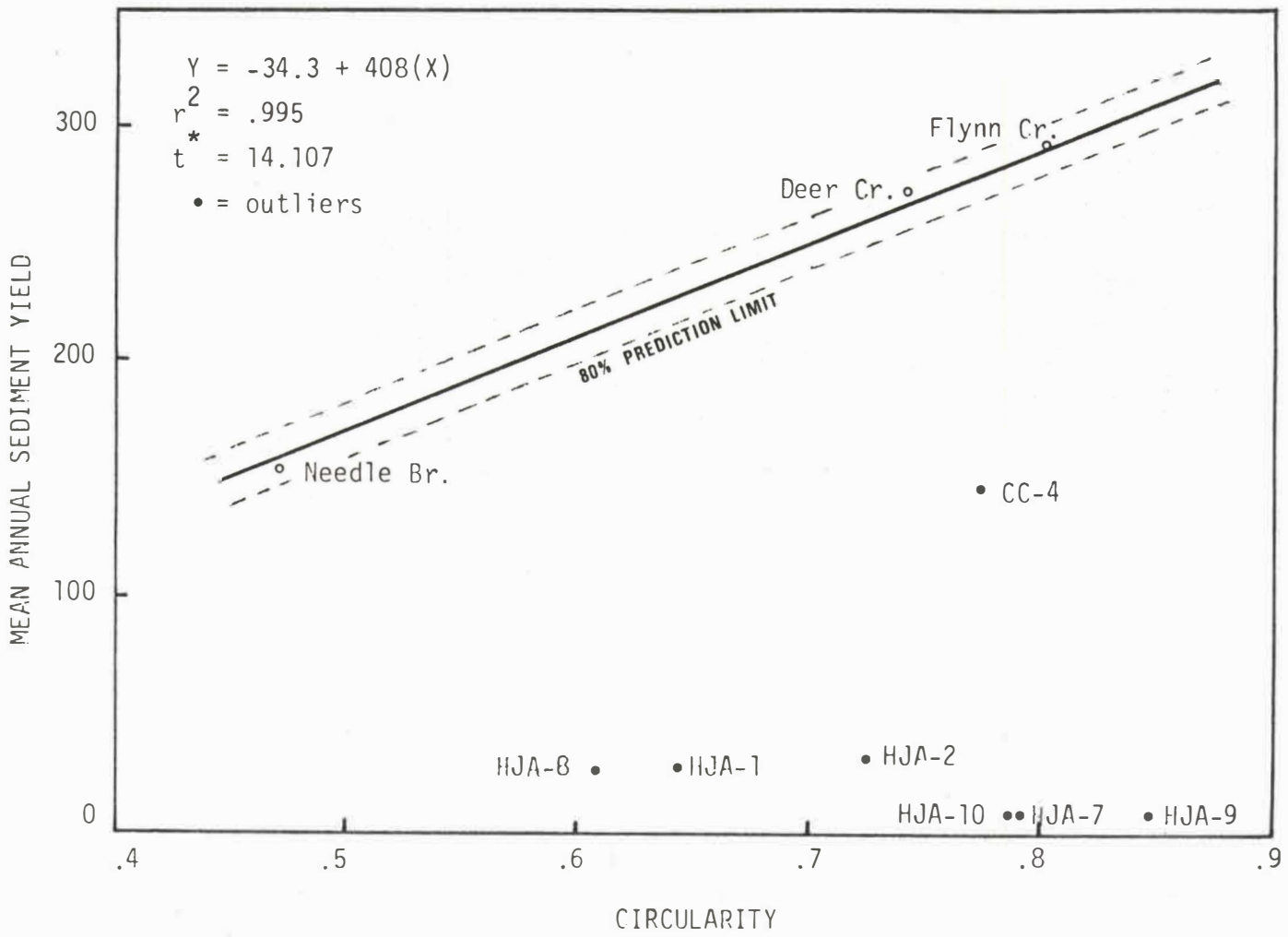

Figure 23. Highly significant correlation of circularity (X) and mean annual sediment yield (Y) for the Alsea Experimental Watersheds. All other study basins are treated as outliers and excluded from the correlation.

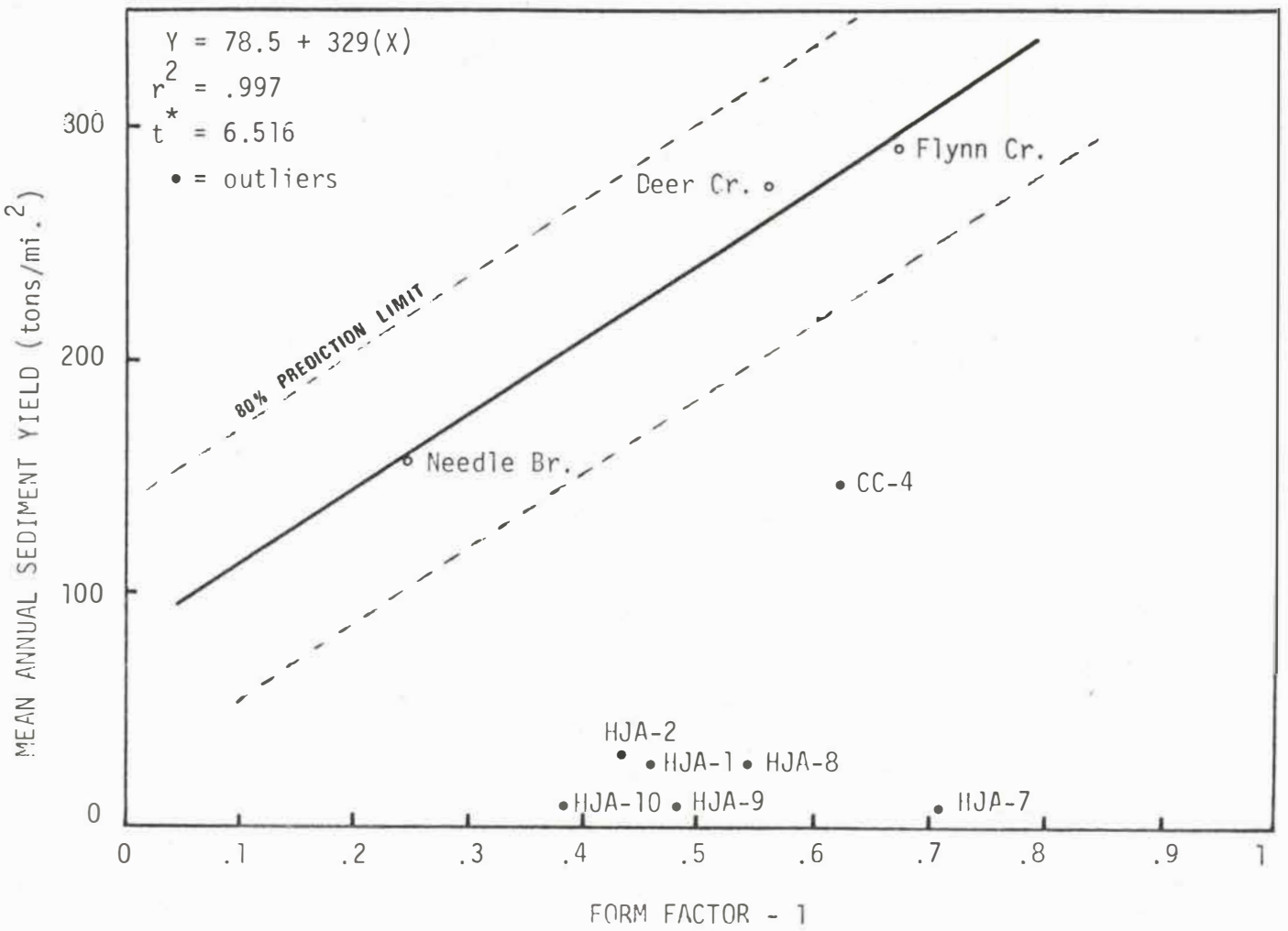

Figure 24. Significant correlations between form factor-1 (X) and mean annual sediment yield (Y) for the Alsea Experimental Watersheds. All other study basins are treated as outliers and excluded from the correlation.

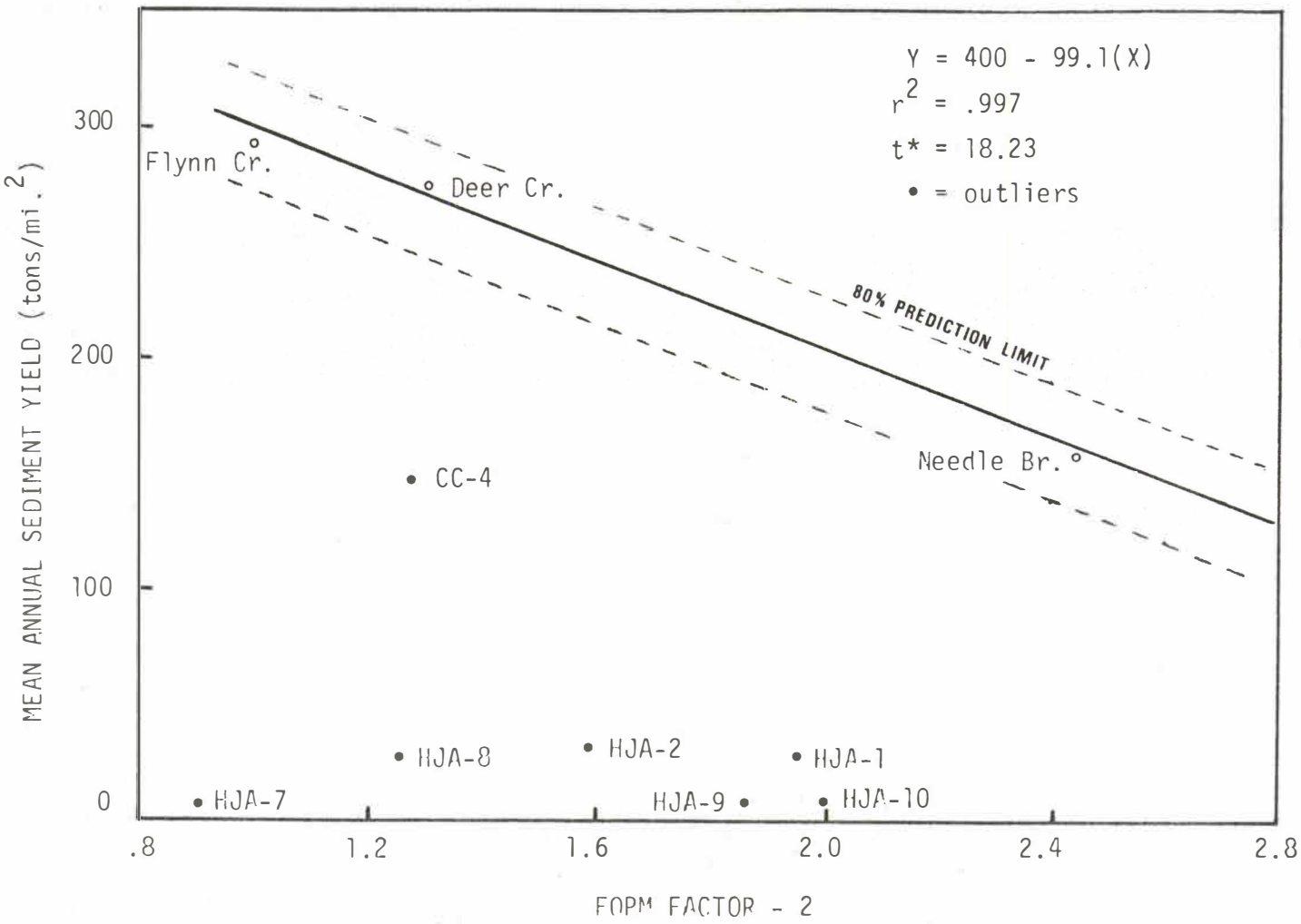

Figure 25. Highly significant correlation between form-factor-2 (X) and mean annual sediment yield (Y) for the Alsea Experimental Watersheds. All other study basins are treated as outliers and excluded from the correlation.

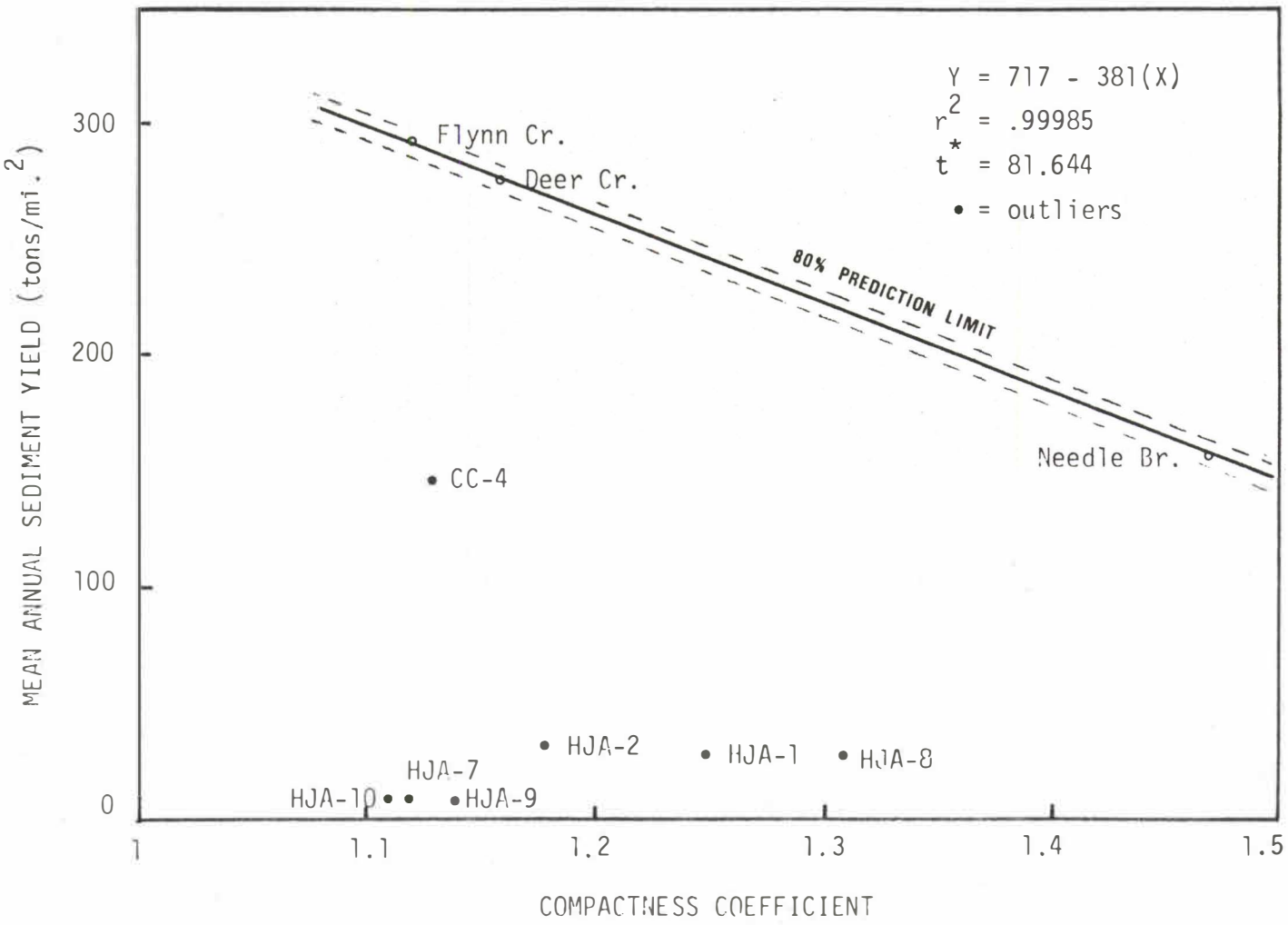

Figure 26. Highly significant correlation between compactness coefficient (X) and mean annual sediment yield (Y) for the Alsea Experimental Watersheds. All other study basins are treated as outliers and excluded from the correlation.

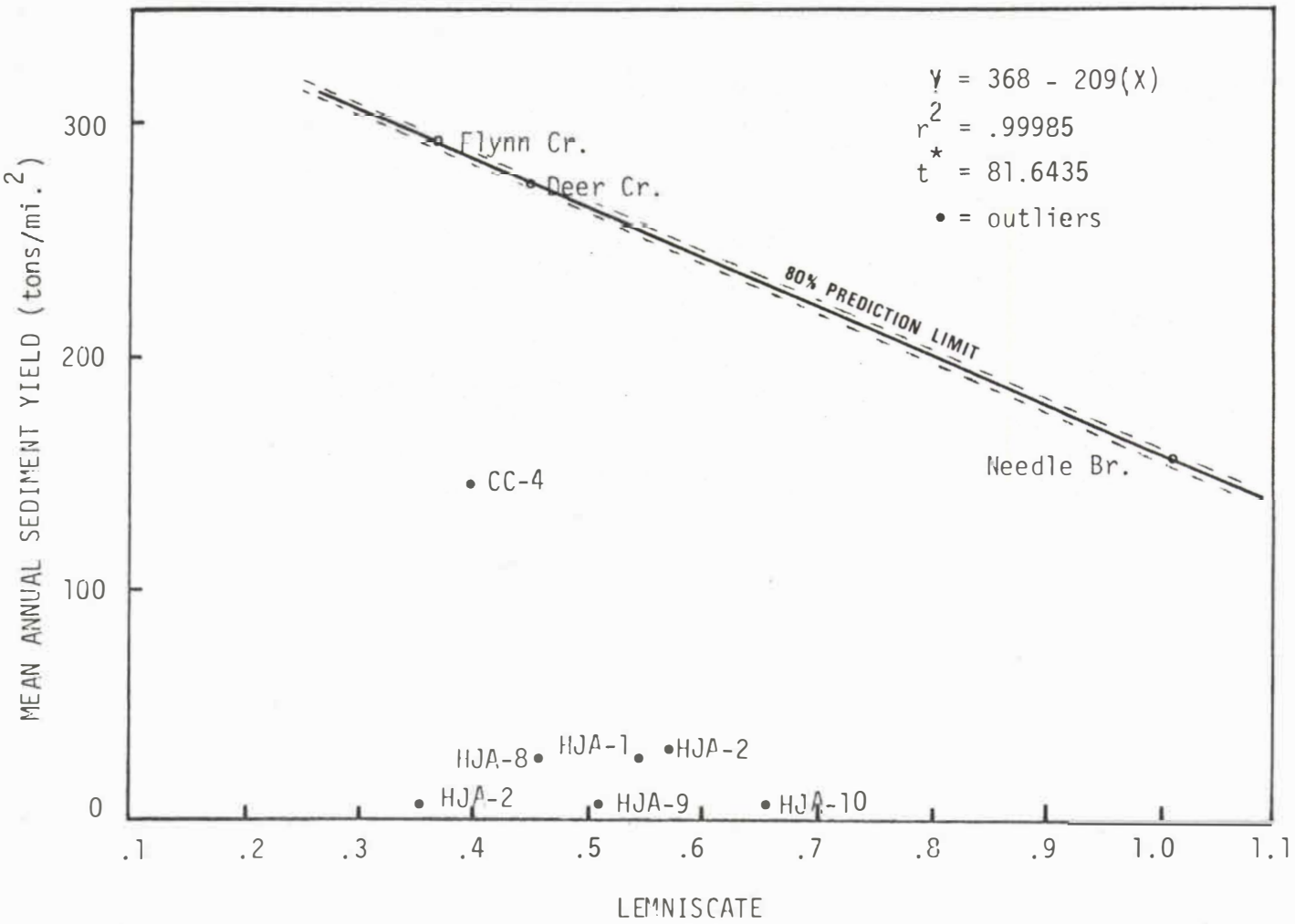

Figure 27. Highly significant correlation between lemniscate (X) and mean annual sediment yield (Y) for the Alsea Experimental Watersheds. All other study basins are treated as outliers and excluded from the correlation.

ment yield, respectively. These morphometric indices may be used to estimate streamflow and sediment yield in the study basins. They may also be used to predict streamflow and sediment yield in a different spatial context. To facilitate the use of the correlations for predictive purposes, eighty percent prediction limits have been sketched for each relationship. For each prediction of streamflow or sediment yield in a new basin, one can be eighty percent assured that the actual value will lie between the prediction bands for a given value of the morphometric variable.

CONCLUSIONS

Linear correlation analysis between single morphometric variables and mean annual runoff, base flow, mean annual peak flow, and mean annual sediment yield reveal several highly significant and physically sound relationships. The direct correlation between drainage density and mean annual runoff reflects the fact that greater channel incision will reduce groundwater storage and afford a more efficient removal of basin precipitation. A higher relief ratio implies that a greater hydraulic gradient exists to promote more efficient basin runoff, thus reducing groundwater storage and base flow. Stream frequency is also an index of the amount of channel incision such that a direct correlation with mean annual peak flow seems reasonable. Drainage density, for similar reasons, is a reliable index of mean annual sediment yield.

The regression equations derived for each relationship consider the morphometric variable as the independent factor with the streamflow and sediment yield considered as the dependent factor, despite the fact that they actually vary together. The application of these equations in a new spatial context constitutes a predictive model. The rather wide prediction bands for each correlation serve to note that the selected morphometric variables are simply indices of streamflow and sediment yield. The complex multivariate nature of basin and stream network controls on hydrological and erosional processes tends to render any one morphometric index of streamflow or sediment yield as tentative. Extra-

polation of streamflow and sediment yield should be avoided when values for the morphometric variable are far removed from the graphical relationship. It is likely that morphometric measurements for the same variable will differ sharply between the study basins and areas in physiographic land types not represented in the present study. It cannot be stated that basin and stream network morphology provides a similar index of streamflow or sediment yield in untested basins subject to contrasting climatic and lithologic controls. Moreover, the correlations are based on data from unlogged watersheds and therefore represent a baseline against which management impacts on hydrologic and erosional processes can be incorporated.

Responsible users of the derived correlations will adhere to the guidelines for mapping, measurement, and statistical analyses discussed in the present study in order to maintain accuracy and consistency for planning purposes. Given the constraints on predictive modeling of streamflow and sediment yield using morphometric variables, the use of the strongest correlations for land management planning on the Siuslaw National Forest is encouraged. Continuing research will identify statistically significant correlations using combinations of several morphometric variables in order to further improve the ability to predict background, long-term average values for annual runoff, base flow, annual peak flow, and annual sediment yield.

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